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REPAIR OF LEAKS IN AN AEROSPACE ENVIRONMENT

TECHNICAL DOCUMENTARY REPORT NO. ASD-TDR-62-1015

February 1963

Directorate of Aeromechanics
Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

PROJECT NO. 8170, TASK NO. 817005

(Prepared under Contract No. AF 33(657)-7852
by the General Electric Co., Philadelphia, Pa.;
D. J. Withey, author.)

NOTICES

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Aeronautical Systems Division, Dir/Aeromechanics, Flight Accessories Lab, Wright-Patterson AFB, Ohio.
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Unclassified report

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(over)

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2. Plastic seals
3. Adhesive seals
4. Spacecraft leakage

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VI. Aval fr OTS
VII. In ASTIA collection

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Liquid sealant that cures to plastic film is used to repair junctions of component and cabin wall. Small punctures are repaired best with putty sealant that cures to form a tough, resilient plug. A self-brazing plug is optimum for larger punctures. Repairing large punctures in tight corners, a metal patch mechanically secured is optimum.

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FOREWORD

This report was prepared by the Missile and Space Division of the General Electric Company, Philadelphia, Pennsylvania, under Contract No. AF 33 (657) - 7852 with the Flight Accessories Laboratory, Aeronautical Systems Division, AFSC. The work was performed in support of Project No. 8170, "Logistics, Maintenance, & Support Techniques," Task No. 817005, "Repair of Leaks in an Aerospace Environment." The work on this study was started on 19 February 1962 and completed on 12 October 1962. The contract monitor was Mr. Earl Washburn, Engineer, Logistics, Maintenance and Support Techniques Section, Support Techniques Branch, Flight Accessories Laboratory.

ABSTRACT

The purpose of this study program was to determine the optimum method for the detecting, location and repair of leaks in a manned space vehicle cabin. The hazards existing in the aerospace environment that could cause leaks were defined. The requirements for the system were established and an optimum system evolved from a trade off of many proposed techniques. The optimum system utilizes cold cathode ionization gauges mounted on the outside (i.e., vacuum or space side) of the cabin wall to detect leakage through the wall by sensing a minute increase in pressure. Separate warning indicators are mounted in back of the detectors, on the inside of the wall. Thus, when a leak occurs, the crew immediately knows the general location of the leak. The area of wall coverage for each detector-warning unit, and thus also system weight, as well as the minimum detectable leak can be varied to suit an individual vehicle. Location of small leaks and faulty seals is accomplished by using helium as a tracer gas. When a small jet of helium is directed over the leak, the current in the detector will drop. Larger leaks would be pin-pointed visually, and/or by the audible noise generated. A decompression warning system is also provided to signal the presence of the very large punctures.

Repair of seals can be accomplished best by the application to the junction of the component and cabin wall of a liquid sealant that cures to form a plastic film. Repair of small punctures, up to the size that creates a cabin decompression, is best obtained with a putty adhesive sealant that cures to form a tough, resilient plug. A self-brazing plug is optimum for the repair of larger punctures. This plug contains a chemical heat source and brazing material that can automatically braze the repair in place. For repair of large punctures in tight corners, however, a metal patch mechanically secured is optimum.

This technical documentary report has been reviewed and is approved.

H. E. Amli

H. E. AMLI, Chief
Support Techniques Branch
Flight Accessories Laboratory

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I. INTRODUCTION

Future astronauts will travel through space confined within a sealed pressure vessel. Inside this pressure vessel, or space cabin, will be provided a life sustaining atmosphere of oxygen and, most probably, a diluent gas. Many hazards exist that could cause impairment of the pressure integrity of the cabin, and resultant loss of the atmospheric gases. This leakage, if allowed to continue, would cause premature depletion of the gas supplies and result in an abort of the mission, or loss of the crew.

Therefore, a means for preventing this excessive loss of atmosphere is desired. Accordingly, this study was initiated to determine the optimum method for detecting, locating and repairing leaks in a manned space vehicle cabin. Generally, the results of this study are concerned with the following: (1) determining and defining the dangers existing in the aerospace environment that could cause leaks in manned spacecraft, (2) establishing the requirements for a leak detection, location, and repair system, (3) defining methods and techniques that could be used for detection, location and repair of leaks, (4) selection of the optimum system, and (5) establishing the feasibility and design concepts for a leak detection, location and repair system.

The system parameters are developed for two different representative space vehicles, one a relatively small three man vehicle of modest mission duration; and two, a relatively large space station of long mission duration. The system design is flexible so that it can be applied to different spacecraft, although some of the operating parameters will depend on the particular design of the vehicle in question.

The system can be integrated into the overall vehicle with little conflict with the vehicle design except for two major points. One, the vehicle must be designed so that the cabin wall is accessible for both locating and repairing of leaks. Thus all equipment, flooring, etc., normally stowed against the wall must be designed to be removable; two, cabin seals for rotating, reciprocating or otherwise moveable shafts must be designed with special provisions for repair, through replaceable seals, or additional spare seals that can be installed on the existing structure. Repair methods developed in this study cannot provide for repair of these seals unless it is desired to immobilize the moveable shaft.

Optimum repair methods are developed in the study for the repair of seals, small punctures and cracks, and large punctures of the cabin wall. Development of the actual liquid and putty sealant material (which presents the optimum method of repair for seals and small punctures, respectively) is not undertaken in this study, however. An outline for an applied research test program to determine the best suited material, as well as suggestions for materials that would be applicable, are given in the text.

This manuscript was released by the author November 1962 for publication as an ASD Technical Documentary Report.

II. DANGERS

2.1 INTRODUCTION

There are many dangers existing in the aerospace environment that could cause leaks in the hull of a manned space vehicle cabin. The most publicized danger is, of course, the probability of a meteoroid puncturing the pressure cabin. While this danger is real, and certainly important, there are other hazards that must be considered also. Elastomeric seals exposed to the hard vacuum of space may, in time, degrade and create leakage. Other structural failures such as collision during rendezvous, abnormal stresses from launch, boost or in flight maneuvers, internal fire or explosion, or random design failure could also distort seal surfaces or rupture the cabin and thus create leakage. This section of the report determines and defines the dangers which exist in the space environment that could cause leaks in manned spacecraft.

2.2 METEOROIDS

Meteoroids are small, numerous bodies of extraterrestrial material that are travelling through interplanetary space. Their origin is thought to be in the asteroid belt that lies between Mars and Jupiter, in the debris from comets, and in the cosmic dust from within our solar system. There are three general types of meteoroids: stony, iron and porous. Stony and iron meteoroids are the best known, having been found on earth after their fall through the atmosphere. The estimated density of a stony meteoroid is about 3.0 grams/cm^3 and for an iron meteoroid is about 8.0 grams/cm^3. The stony type is thought to outnumber the iron meteoroid by a factor of 9 to 1. The average composition of these meteoroids is given in Table 1.

TABLE 1. AVERAGE COMPOSITION OF METEORITES

IRON		STONE			
Fe	90.66%	O	36.40%	C	.15%
Ni	8.48%	Fe	23.38%	Cr	.03%
Co	.59%	Si	18.20%	Mn	.24%
P	.17%	Mg	13.80%	Co	.17%
S	.04%	S	1.80%	K	.17%
C	.03%	Ca	1.70%	Ti	.11%
Ca	.02%	Al	1.50%	P	.11%
Cr	.01%	Ni	1.50%	Cl	.08%
		Na	.65%	Cu	.01%

A meteoroid is called a meteor when it becomes luminous due to frictional heating as it passes through the atmosphere. Much of the information available about the population of meteoroids in space is deduced from the observations of these meteors. In order of increasing size, they are called telescopic meteors, visual meteors, photographic meteors and fireballs. The limits of these sizes is roughly from 0.03 cm to 10 cm equivalent radius. Meteors at greater than 10 cm equivalent radius usually reach the earth with a portion of their mass intact and when thus found are called meteorites.

The concept of porous meteoroids is relatively recent and is derived from visual sightings of meteors. With the increasing knowledge of properties of the upper atmosphere, it became apparent that some meteors disappeared at much greater altitudes than would be expected from a solid iron or stony meteoroid. From analysis, it was determined that these meteors could be loosely bound agglomerates of smaller dust particles. These "dust balls" collapse under small aerodynamic load whereupon they are converted into a cloud of dust which vaporizes quickly due to the increased surface area. Their density is about 0.05 grams/cm^3.

Meteoroids smaller than 0.03 cm equivalent radius are called micrometeoroids. Their radii seem to extend down to 10^{-4} cm at least. Micrometeors are too small to be seen by visual means and because of their small size reach the surface of the earth with little loss of original mass. Here, they can be collected and identified from deep sea clay as "cosmic spherules". Their size and population density can also be estimated from calculating light-scattering effects (zodiacal light). The total mass of micrometeors per volume of space exceeds that of all other meteors taken together. Data on the size and masses of meteoroids corresponding to densities of 0.05, 3, and 8 grams/cm^3 appears in Figure 1. The diameter of the meteoroid is calculated on the basis of its being a sphere. Actual meteoroids will deviate markedly from sphericity and will also vary markedly in mean density. There is no single relationship between the magnitude of a meteor, as determined by visual, photographic or radio means, and the mass, however. Various assumptions are used to establish this relationship resulting in the multiple curves of Figure 2.

The population density of sporadic meteors is shown in Figure 3 as the number of impacts per second per square meter of exposed area of meteoroids of a given mass or greater, versus mass in grams. Several estimates are shown and vary over 3 orders of magnitude. The effect of altitude on meteoroid population is not considered, although such theories exist, because it would be small in comparison to the difference in these estimates. Rocket and satellite data are included also. These data are collected by means of different sensors such as crystal microphones, phototubes or wire grids set to indicate impacts with momentum or kinetic energy above their

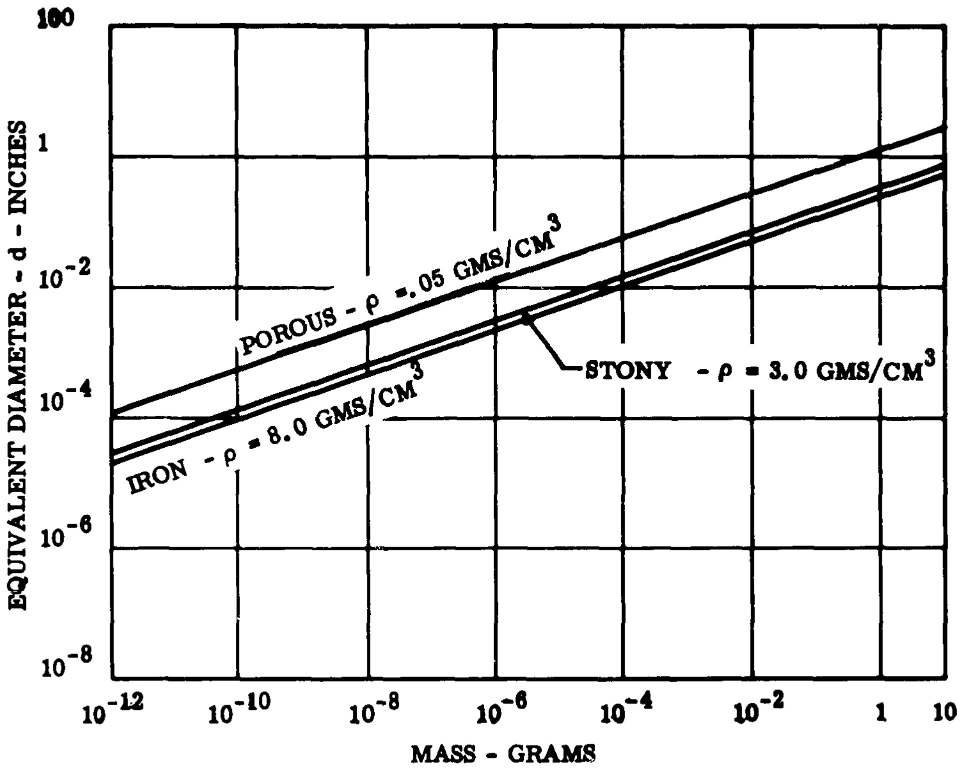


Figure 1. Equivalent Diameter of Meteoroids Vs. Mass

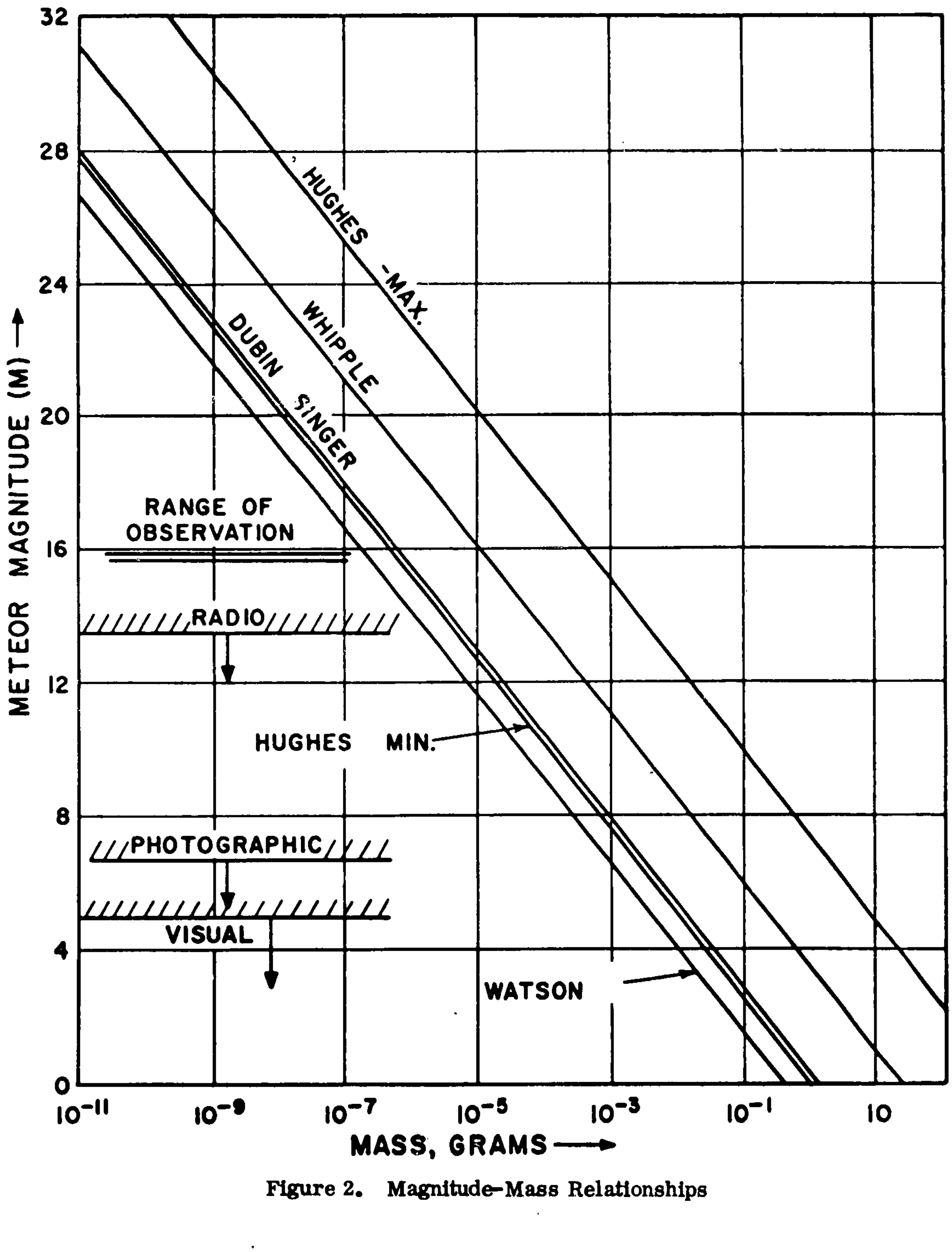


Figure 2. Magnitude-Mass Relationships

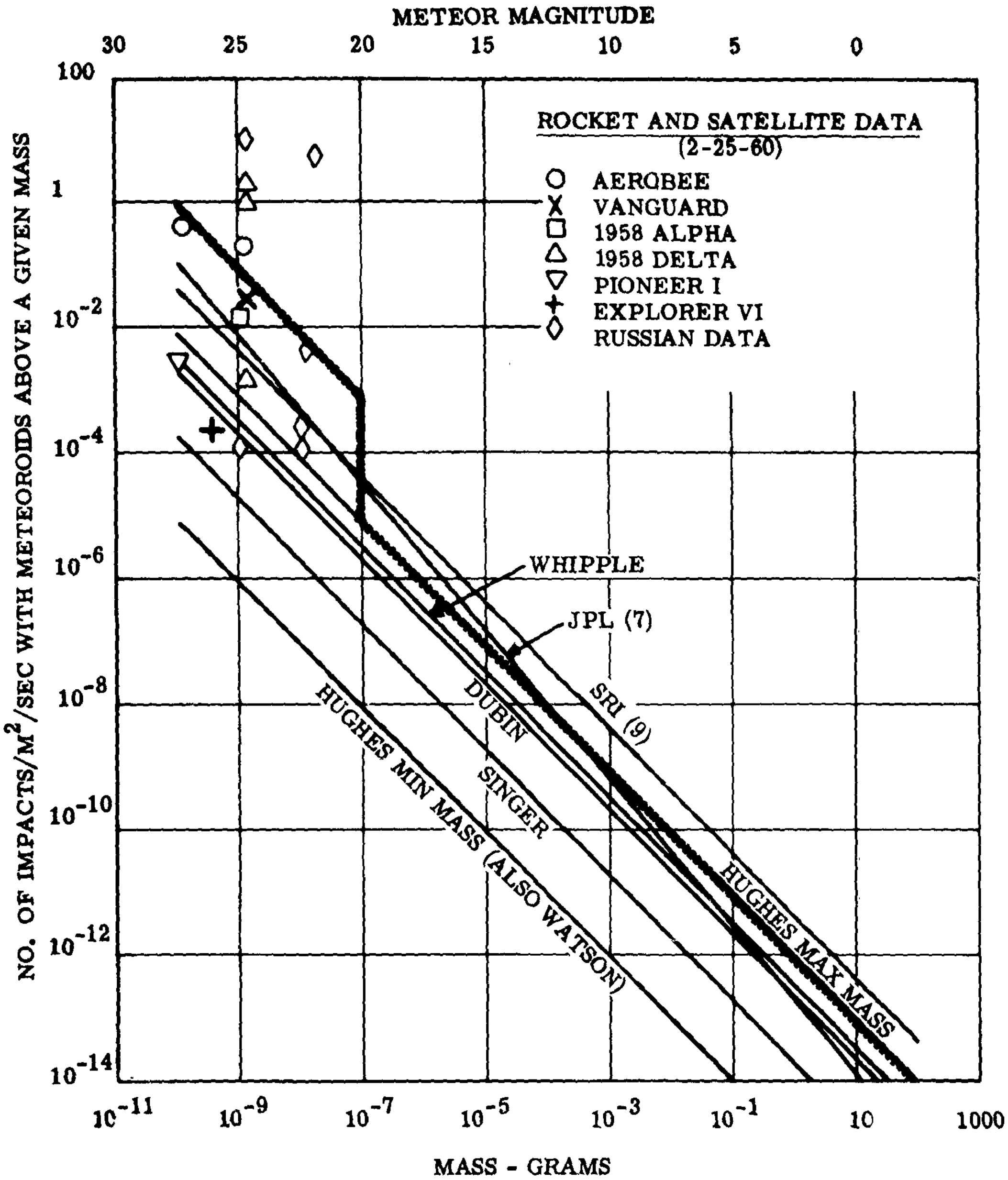


Figure 3. Meteoroid Population Estimates

threshold actuation level. The wide scatter in the data is attributed to differences in interpretation of the readings (since calibration is performed at low velocities with relatively large particles) and to spatial and temporal differences in sampling conditions.

The population from Reference 9 is the most conservative for the larger meteoroids, whose penetration effects are of primary interest. The large meteoroid population estimate of Reference 9 is perhaps too conservative because it correlates rocket and satellite data of very small meteoroids with the same slope curve that correlates meteors of larger masses (i. e., radio, photographic and visual meteors). Since the rocket and satellite data have generally produced higher population densities of the small micrometeoroids than predicted by extrapolated curves based on meteors (earth-bound observations), this leads to slightly overestimated population densities for the larger meteoroids. A more reasonable approach, perhaps, is that of Reference 7, where satellite data is also included but the slope of the curve is increased to correspond to the observations of the larger meteors. Because of the uncertainties involved, it is recommended that the crosshatched curve of Figure 3 be used to estimate impact effects for conservative estimates. This curve represents the "Hughes-maximum mass" data plus an extension to include the bulk of the satellite data.

Meteoroid showers represent a greater hazard to space vehicles than sporadic meteoroids, since they have a much higher frequency of impact. Table 2 presents some meteor shower information on annually recurring showers, and Table 3 presents further representative data on meteor showers (Ref. 1). It should be noted that only those showers which intersect the earth's orbit can be detected. There may be others. Some of these meteoroid showers can be avoided by choosing a takeoff time such that the vehicle's path will not intersect with the showers. In general, this may be difficult because the appearance and duration of the meteoroid showers is so spread out that it might not be practical to avoid them.

Column 4 of Table 2 refers to the radiant angle described by two angles, right ascension (R. A.) and declination (Dec.), which are the celestial coordinates. The radiant angle of the meteoroid shower is measured like any other star (which is the reason why they are usually given the name of the nearest star). The vertex of the radiant angle is that point from which the meteoroid shower radiates (shown in Figure 4).

2.2.1 Meteoroid Penetration

Meteoroid penetration is a function of the relative velocity between the meteoroid and spacecraft as well as a function of the mass of the meteoroid. Meteoroids originating within the solar system have velocities, relative to earth, between 11 km/sec and 73 km/sec

TABLE 2. ANNUALLY RECURRING NORTHERN HEMISPHERE METEOR STREAMS

STREAM	Date at Maximum	Extreme Limits	Radiant R. A. Dec. 1950	Velocity in Atmos. km sec^{-1}	Stream Hourly Rate at Maximum			Transit of Radiant (Local Time Midnight $=00^h$)
					Radio	Visual	Photo.	
Quadrantids	Jan. 3	Jan. 1-4	230 +48	38.5	95	30	1.9	$8^h\ 28^m$
Aurigids	Feb. 9	5 days?	75 +42	--	--	5	--	$19^h\ 43^m$
Virginids	March 13	16 days?	183 +4	30.8	--	1?	--	$0^h\ 49^m$
Lyrids	April 22	2 days	270 +33	48.4	9	5	--	$3^h\ 59^m$
η Aquarids	May 4	10 days	336 +0	64	15	5	--	$7^h\ 36^m$
Arietids	June 8	May 29-June 18	44 +23	38.0	66	--	--	$9^h\ 51^m$
ζ Perseids	June 9	June 1-16	62 +23	28.9	42	--	--	$10^h\ 59^m$
β Taurids	June 30	June 24-July 6	86 +19	31.4	27	--	--	$11^h\ 12^m$
δ Aquarids	July 28	July 24-Aug. 7	339 -17	40.5	34	10	--	$2^h\ 14^m$
Perseids	Aug. 12	July 29-Aug. 17	46 +58	59.2	50	37	2.5	$5^h\ 43^m$
Orionids	Oct. 22	Oct. 18-26	94 +16	65.5	18	13	2.9	$4^h\ 12^m$
Southern Taurids	Nov. 1	Oct. 27-Nov. 22	51 +14	28.1	--	5	--	$0^h\ 40^m$
Northern Taurids	Nov. 12	Oct. 17-Dec. 2	52 +21	29.5	14	5	--	$0^h\ 1^m$
Leonids	Nov. 17	5 days	152 +22	70.8	9	6	--	$6^h\ 22^m$
Geminids	Dec. 13	Dec. 7-15	113 +32	35.9	80	55	5.6	$2^h\ 12^m$
Ursids	Dec. 22	Dec. 22-23	217 +76	37.4	13	15	--	$8^h\ 24^m$
Periodic Stream								
Giacobinids	Oct. 10 1959	1 day	262 +54	23.1	10,000	4200	--	$16^h\ 13^m$

TABLE 3. ADDITIONAL METEOR SHOWER DATA**

Shower	Date	Local Time Visible Rise	Local Time Visible Set	Hourly Rate Visual	Hourly Rate Radio	Velocity, km/sec	Period, Years	Next Maximum
Cygnids	January 17	0230	2130	-	-	-	-	-
Bootids	March 10-12	2200	0830	-	-	-	-	-
Coma Berenices	March 20	1800	0630	-	-	-	-	-
Aquarids	May 1-6	0300	1200	12	12	66	76	1986
Herculids	May 11-24	1800	0630	-	-	-	-	-
Pegasids	May 30	2300	1200	-	-	-	-	-
Scorpiids	June 2-17	2000	0300	-	-	-	-	-
Pons Winnecke	June 27-30	Does not set, min. at 0900		-	-	-	-	-
Cygnids	July 14	1800	1000	-	-	-	-	-
Capricornids	July 18-30	2030	0400	-	-	-	-	-
Perseids	July 25-Aug. 4	2230	1430	-	-	-	-	-
Aquarids	July 26-31	2200	0600	10	22	50	3.6	-
Perseids	August 10-14	Does not set, min. at 1730		50	50	61	108	(Note 1)
Cygnids	August 10-20	1200	0700	-	-	-	-	-
Draconids	August 21-23	Does not set, min. at 0900		-	-	-	-	-
Draconids	August 21-31	Does not set, min. at 0700		-	-	-	-	-
Perseids	September 7-15	2130	1200	-	-	-	-	-
Aurigids	September 22	2100	1230	-	-	-	-	-
Quadrantids	October 2	0500	0000	-	-	-	-	-
Giacobinids	*October 9	0600	0300	(Note 2)		20	6.6	1959

Table 3. ADDITIONAL METEOR SHOWER DATA** (Cont'd)

Shower	Date	Local Time Visible Rise	Local Time Visible Set	Hourly Rate Visual	Hourly Rate Radio	Velocity km/sec	Period, Years	Next Maximum
Arietids	October 12-23	1900	0700	-	-	-	-	-
Orionids	*October 18-23	2230	0930	15	30	68	76	1986
Taurids	November 1-7	1900	0630	10	16	27	3.3	1957
Leonids	November 14-18	0000	1230	12	(Note 3)	72	33.2	1965
Andromedids	November 22-30	1300	0600	(Note 4)		22	6.7	1958, 1959
Geminids	*December 10-14	1900	0900	60	70	35	1.6	(Note 1)
Ursids	December 22	Does not set, min. at 2030		(Note 5) 13	13	38	13.5	1958, 1959
Cetids	*May 19-21	0530	1430	-	-	20	37	-
Perseids	June 4-6	0500	1730	-	-	40	29	-
Arietids	June 8	0330	1530	(Note 6)		70	38	-
Taurids	June 30-July 2	0500	1700	-	-	30	31	-

*** Major showers - Last four are daylight showers**

**** This is not the best data.**

Notes

1. These streams are evenly distributed and little year to year variation is to be expected.
2. Very concentrated stream. Peak years give up to 400 meteors per minute but shower lasts for only 6 hours. During off years the count is negligible.
3. Peak years give 60/hour visual. In the peak years of the 1800's, prior to being deflected by Jupiter and Saturn, this shower gave 1200 per minute.
4. Before being deflected by Jupiter this stream gave peak year rates of 100/minute. No notable rates have been observed since, though the stream could return.
5. Short duration shower. Peak years the radio rate is 165/hour.
6. This intense daylight shower begins June 2 and runs to June 14 with radio rates from 25 to 70/hour.
7. Reference: QST, V51, N4 Apr 1957, p. 20.

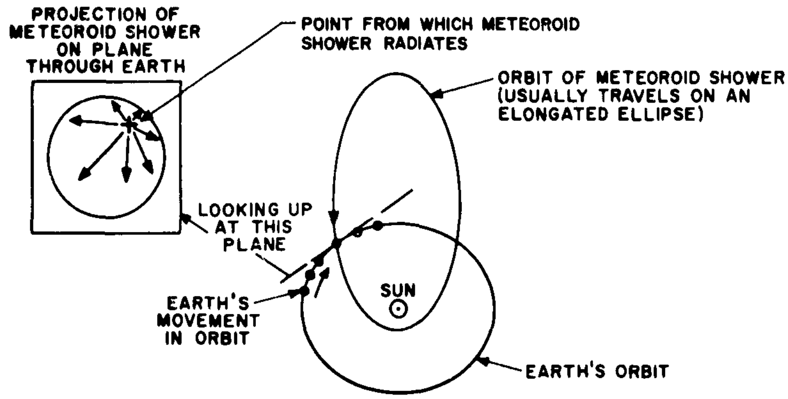


Figure 4. Meteor Shower Radiant Point

(1km/sec = 3281 fps). None have been observed at higher velocities, although flight along a hyperbolic trajectory would imply velocities in excess of 73 km/sec. This latter value is the maximum magnitude of the vector sum of the earth's velocity (29.76 km/sec) and the parabolic heliocentric velocity for a particle at the earth's distance from the sun, plus a small effect of the earth's attraction. The lower limit of 11 km/sec is simply escape velocity from earth.

Figure 5 shows the velocity distribution assumed by Whipple in his calculations of kinetic energy (Ref. 4), Figure 6 shows velocities of sporadic and shower meteoroids as a function of elongation (Ref. 5). Figure 7 compares photographic and radio data (Ref. 1). The photographic data is based on observation of about 100 meteors, whereas the radio data represent several thousand observations. Figure 8 is a histogram showing one sample of the velocity distribution of shower and sporadic meteors.

Kinetic energy is probably the most significant parameter which defines the impact effects of meteoroids on structures. Since kinetic energy is a function of mass and velocity, the assumptions made in regard to velocity will be reflected in the results of the calculation of kinetic energy. Figure 9 shows kinetic energy vs mass for various assumed velocities (Whipple, Singer and Dubin) as well as for the limit velocities of 11 km/sec and 73 km/sec. Note that velocity relative to the moving space vehicle must be used in predicting impact effects and this may be estimated in a manner similar to Figure 6.

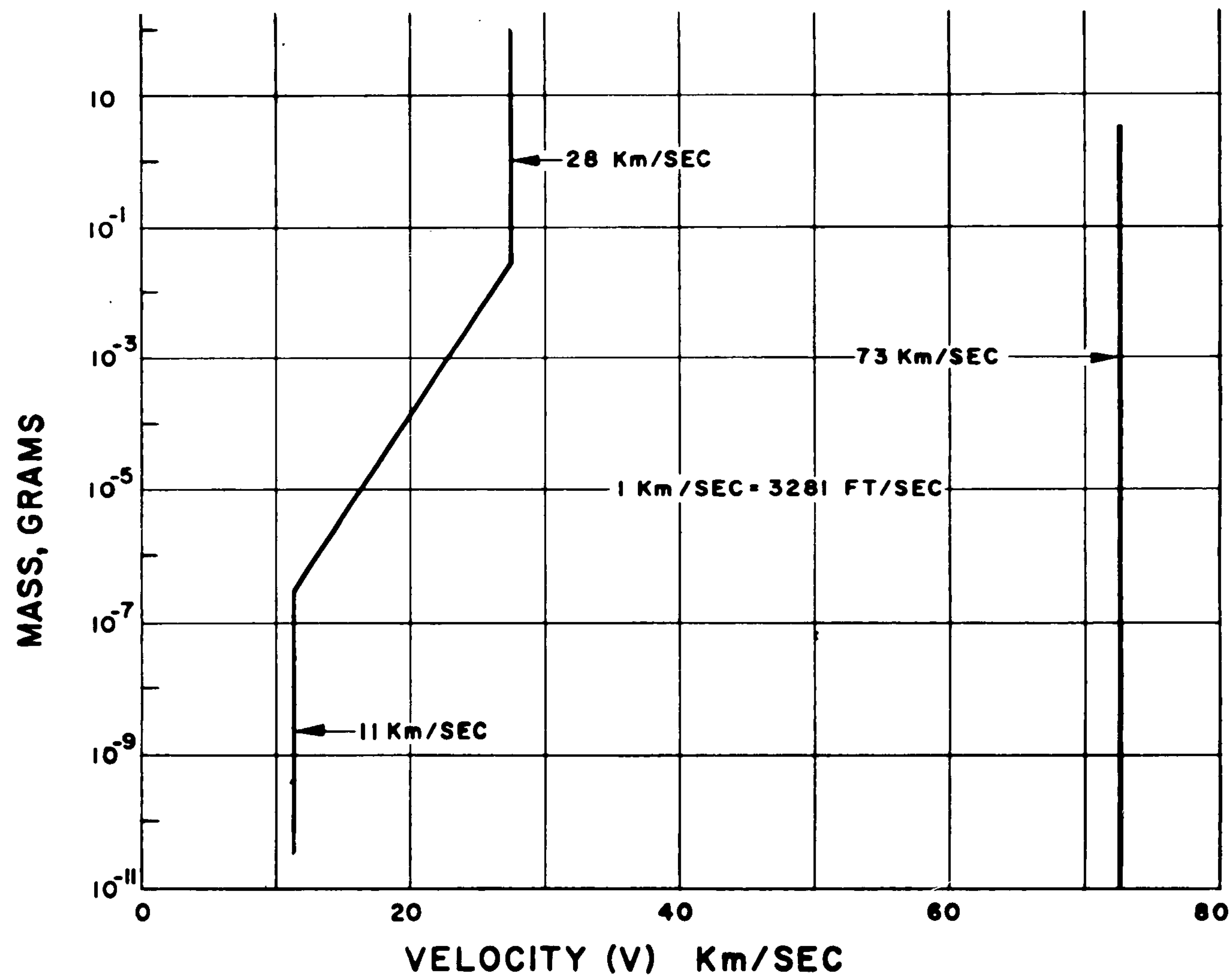


Figure 5. Mass Velocity Distribution Used by Whipple

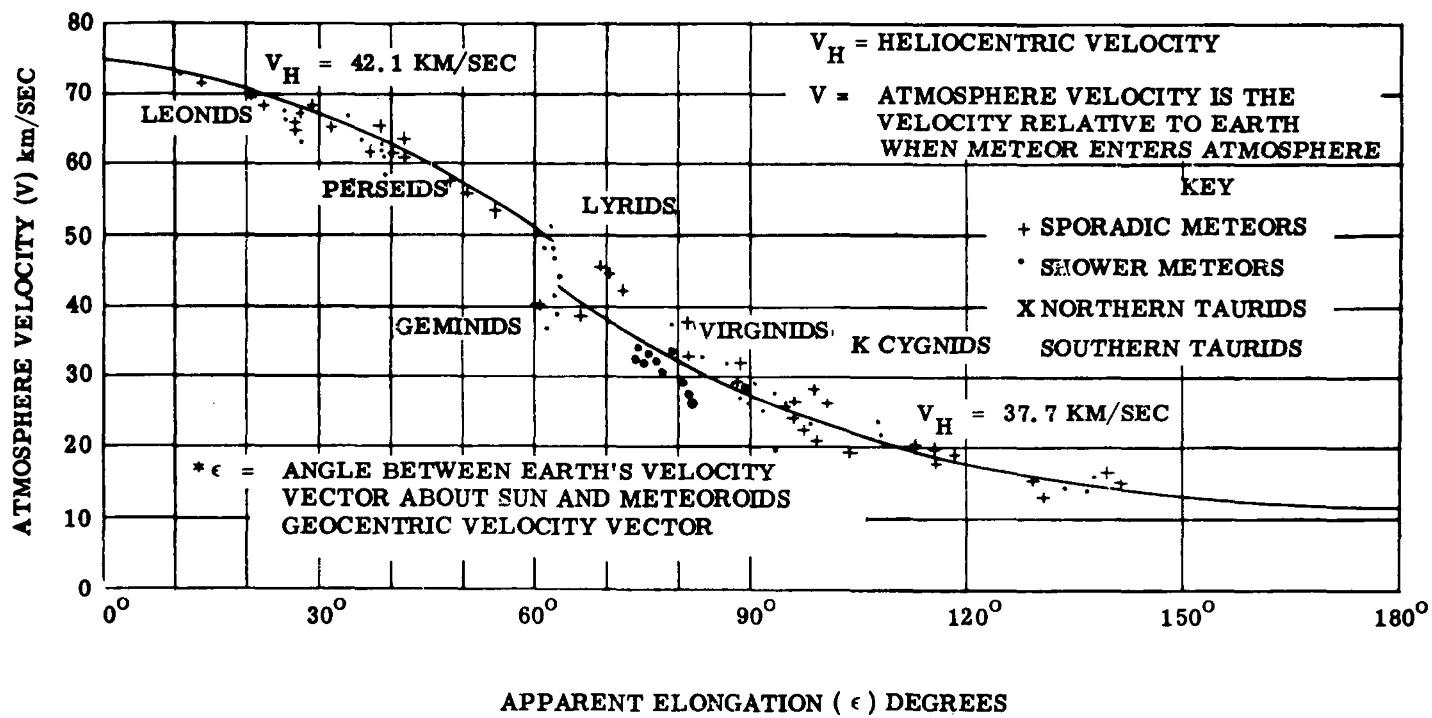


Figure 6. Velocities of Sporadic and Shower Meteoroids as a Function of Elongation

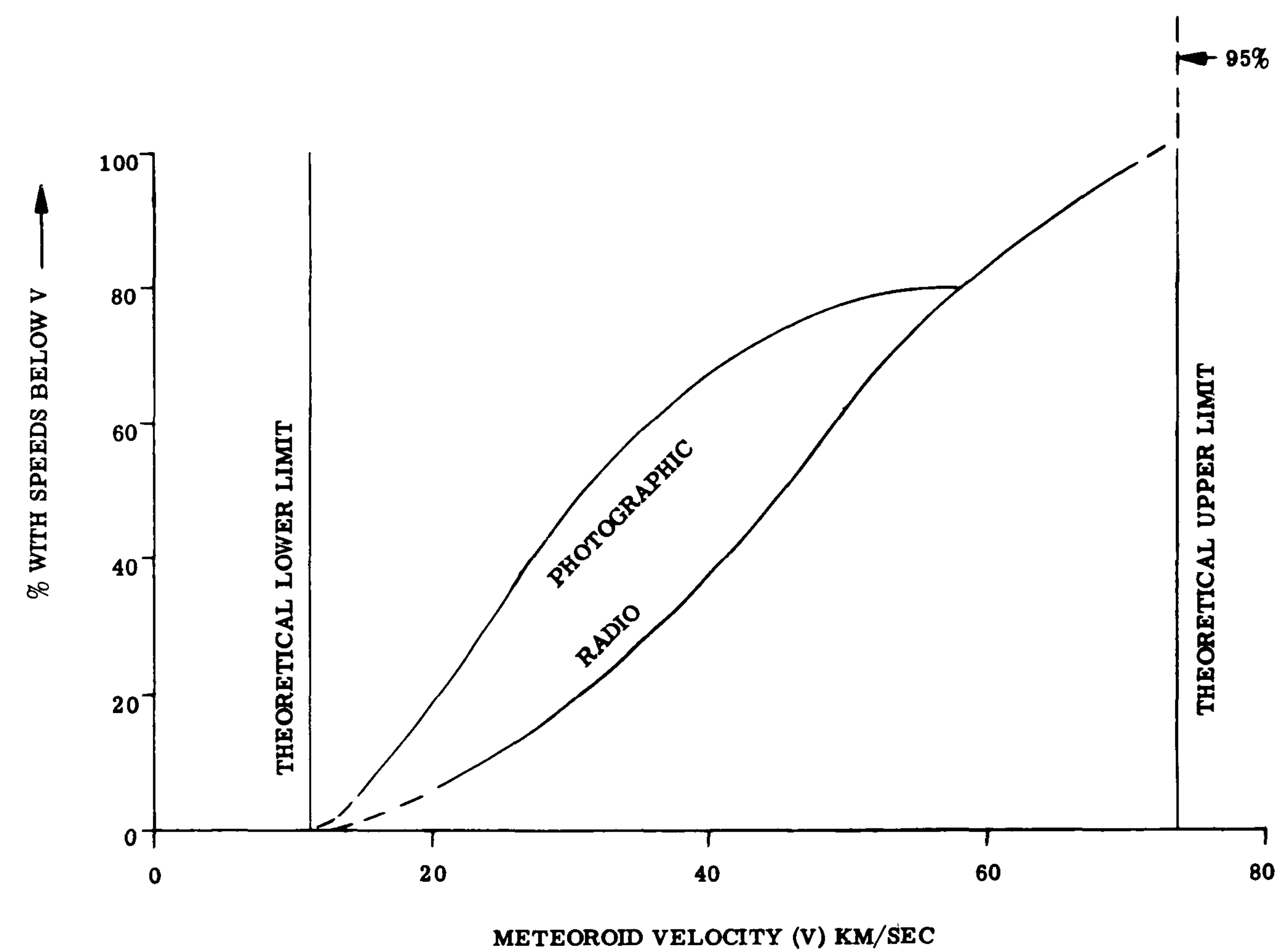


Figure 7. Comparison of Photographic and Radio Data

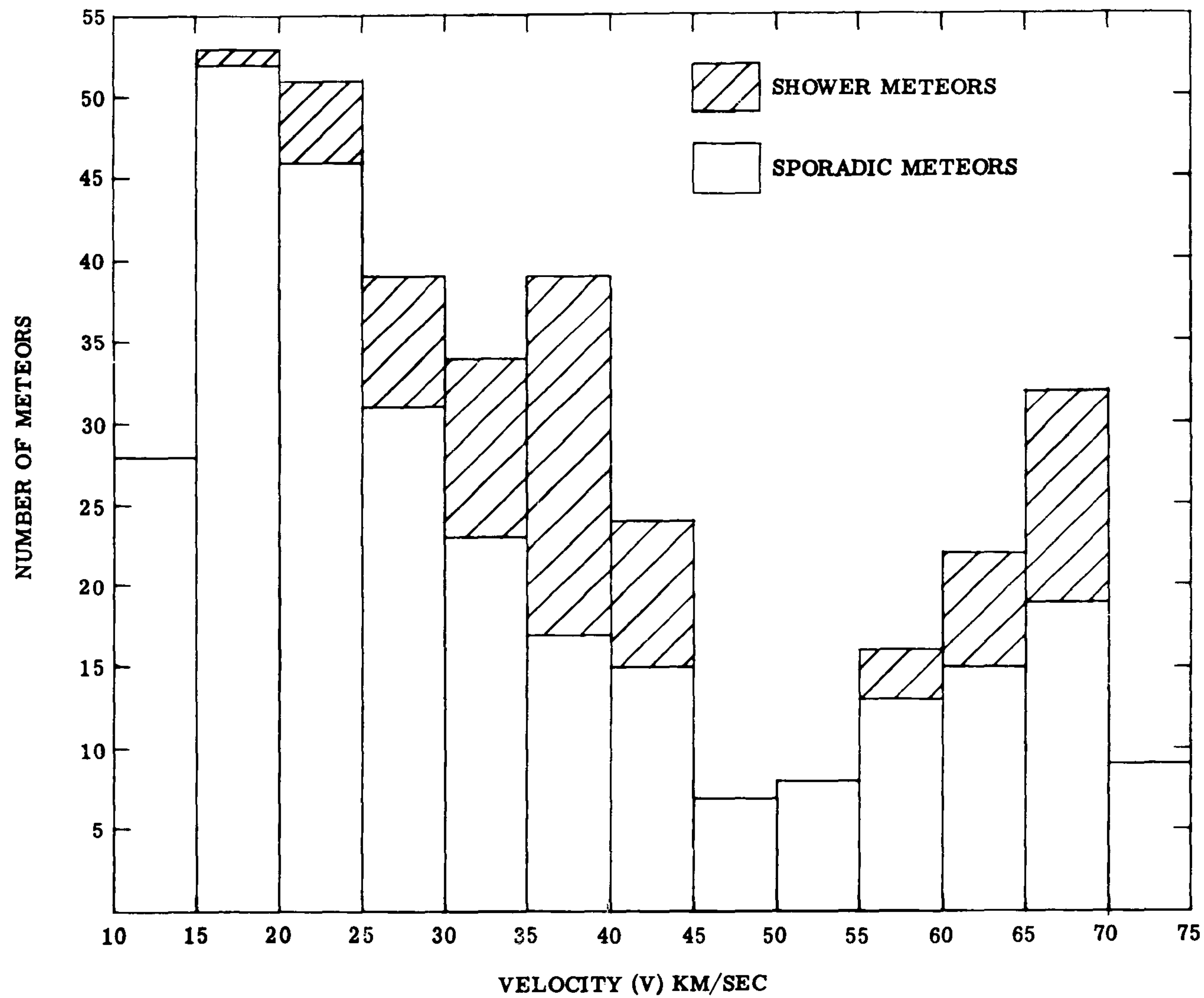


Figure 8. Velocity Distribution of Shower and Sporadic Meteors

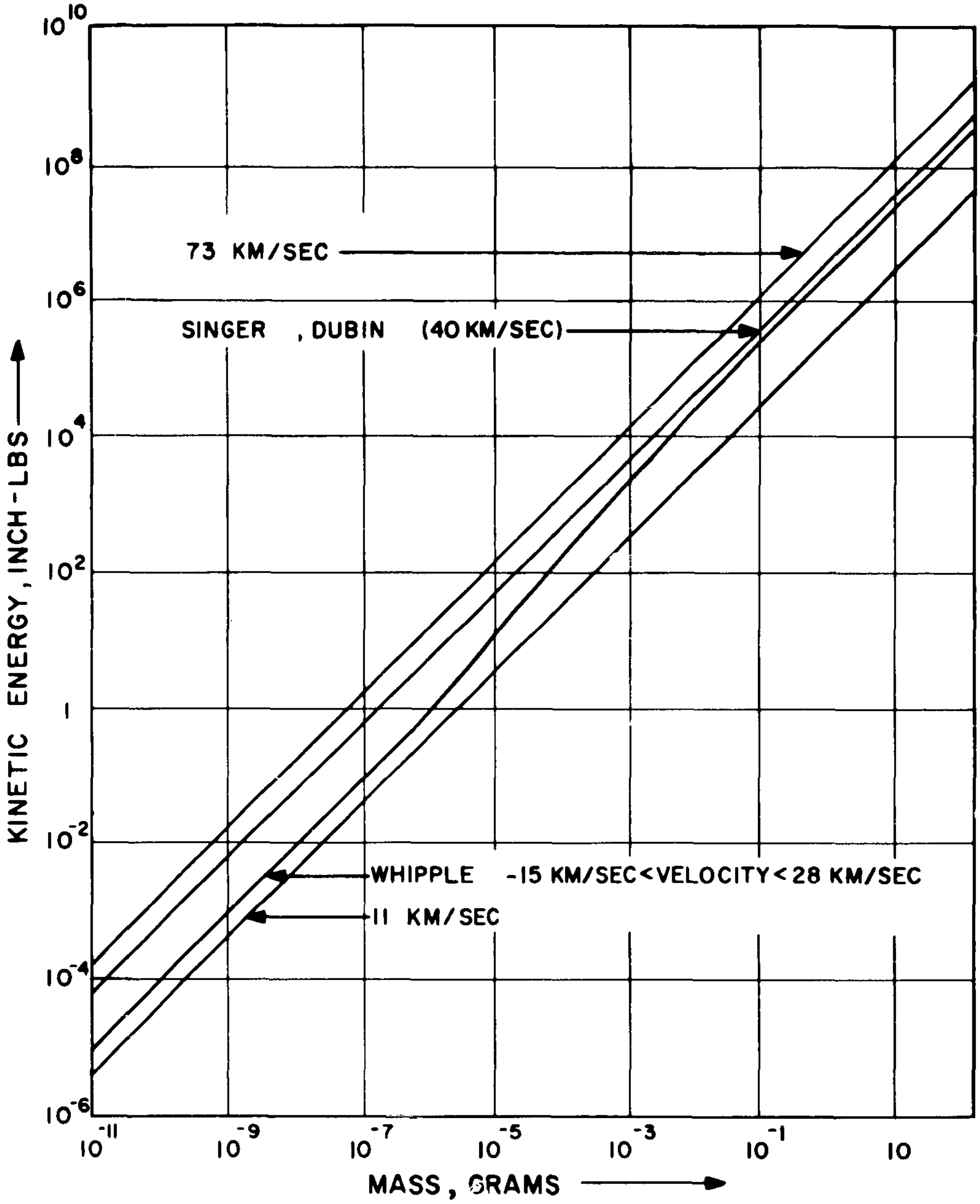


Figure 9. Kinetic Energies of Meteoroids

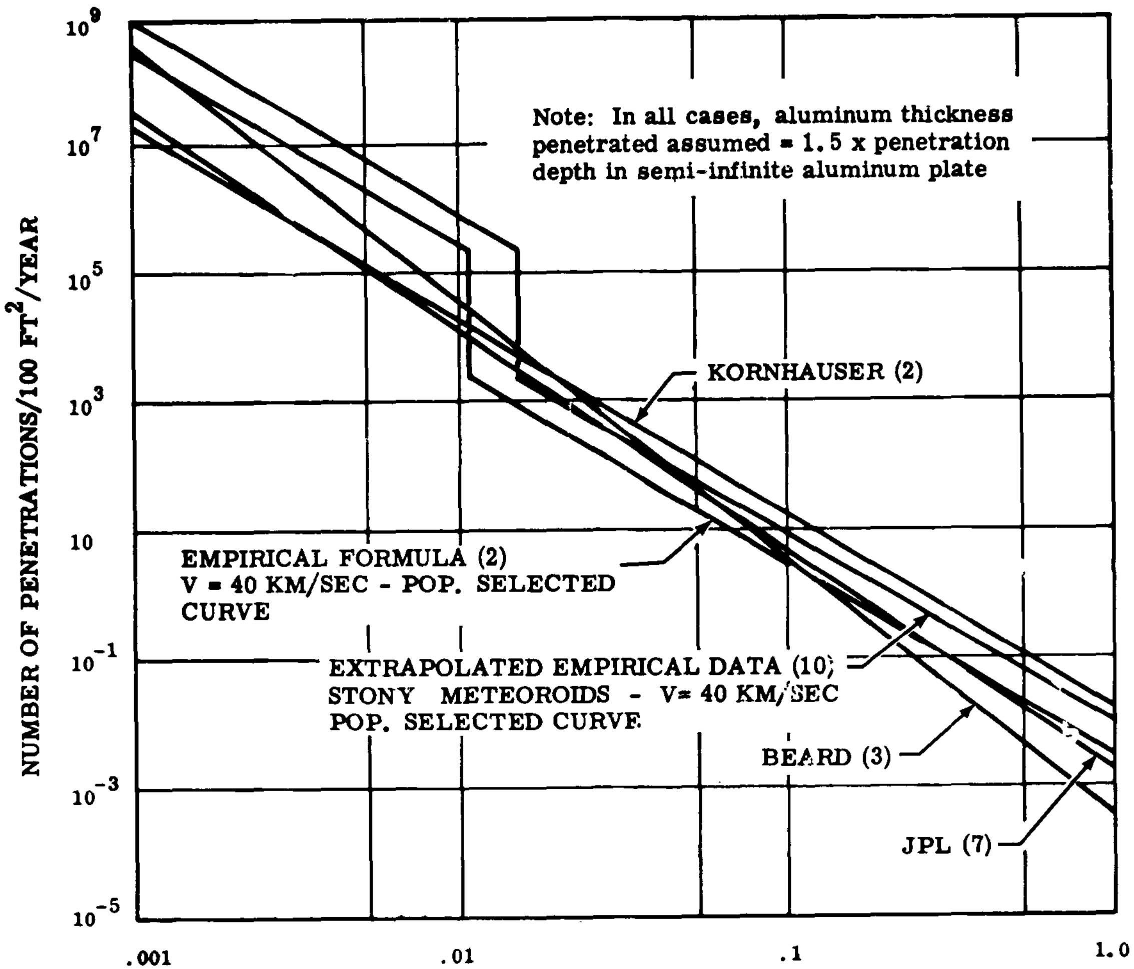


Figure 10. **Estimates of Meteoroid Penetration in Aluminum**

Reference 2 considers the laboratory data on hypervelocity cratering and presents the following empirical formulae which are valid for any consistent set of units. The dimensions given here apply to subsequent calculations.

$$\frac{VE}{U} = 17.5\left(\frac{E}{E_o}\right)^{0.26}$$

$$h = 2\left(\frac{U}{E}\right)^{1/3}\left(\frac{E}{E_o}\right)^{0.09}$$

where

V = volume of crater (in^3)

E = modulus of elasticity of hull material (lbs/in^2)

U = kinetic energy of impacting particle (in-lbs)

E_o = reference modulus = 10^6 lbs/in^2

h = depth of crater (in)

The assumptions and extrapolations (velocity and size) which were necessary in order to arrive at these equations are considered in reference 2 and will not be discussed here except to say that the hull material is assumed to behave as a semi-infinite medium; that is, the craters on a thin skin are the same as those on a thick plate, and the skin is penetrated when h exceeds the skin thickness. The expression for the depth of crater is expected to be correct within a factor of 2 or 3.

Substituting the estimates of kinetic energy given in Figure 9 corresponding to 40 km/sec. into the above equation for penetration depth, and combining with the cross-hatched curve of Figure 3 (meteoroid population density) yields the curve of Figure 10. This figure shows the average number of penetrations expected per year on a 100 ft^2 aluminum surface versus the thickness of the aluminum. Also shown are penetration estimates of Kornhauser (Ref. 2), Beard (Ref. 3), JPL (Ref. 7), and Herrman & Jones (Ref. 10). Kornhauser's estimate is derived from the penetration equation given above on the following kinetic energy basis:

$N = \frac{1}{U}$ = no. of impacts having kinetic energy greater than U (in-lbs) per 10 m^2 exposed area per hour.

substituting $N_h = \frac{8}{Eh^3} \left(\frac{E}{E_o}\right)^{.27} \quad \frac{\text{holes}}{\text{hour - 10 m}^2}$

for aluminum and converting to different units,

$$N_p = \frac{3.2 \times 10^{-5}}{h^3} = \frac{\text{no. of penetrations}}{100 \text{ ft}^2 - \text{day}}$$

The derivation of Beard's equation is given in Reference 3. The resulting equation for depth of penetration, h, is:

$$h = \left[\frac{3 \; m \; V^2}{2 \pi \; d_T \; H_T}\right]^{1/3} \qquad \text{where}$$

m = mass of incident meteoroid, grams

V = velocity of incident meteoroid, cm/sec

d_T = density of target material, gms/cm^3

H_T = heat of vaporization of target, ergs/gram

The assumed meteoroid flux density is:

$$N = 2.0 \times 10^{-5} \; m^{-1.34} = \frac{\text{no.}}{\text{m}^2 - \text{year}}$$

and velocity is assumed as 30 km/sec.

Then for aluminum, and converting to different units:

$$N_p = \frac{6.43 \times 10^{-7}}{h^4} = \frac{\text{no. of penetrations}}{100 \text{ ft}^2 - \text{day}}$$

Reference 7 predicts penetration based on Bjork's theory plus their own population estimate (see Figure 3).

Reference 10 correlates the results of 1,700 data points on hypervelocity impact gathered by 15 separate laboratories and analyzes the results statistically. The fit of the data to a simple power law was investigated, with the resulting equation:

$p/d = kK^{2/3}B^{1/3}$

p = penetration; d = projectile dimension; $K = \rho_p/\rho_t$, the projectile to target density ratio; and $B = \rho_t V^2/H_t$ where V is the projectile velocity and H_t the Brinell Hardness of the target. The value of k is 0.36 for most materials.

The above equation is limited to normal incidence impacts on a quasi-infinite metal target in the high velocity impact range. In high velocity impact, the penetration is dependent on the velocity to the 2/3 power. On the other hand, penetration at low velocity is dependent on the velocity to the 4/3 power, and it is speculated that penetration at hypervelocity is dependent on velocity to the 1/3 power. Thus a logarithmic type of equation was sought which would correlate the empirical data, the bulk of which was in the high velocity region and transition region between low and high velocity, and contain the proper velocity exponent. Theoretical predictions of several workers were investigated and it was found that only the theory of Bohn and Fuchs showed reasonable agreement with the empirical data. A correlating equation, based on Bohn and Fuchs work, was then determined and is:

$$p/d = k_1 K^{2/3} \log_e \left(1 + \frac{K^{2/3}B}{k_2}\right)$$

$k_1 = 0.6$ and $k_2 = 4$ for most materials

Because of the very limited physical basis for the above equation, extrapolation to the hypervelocity region is dangerous, and could lead to erroneous results. However, extrapolation was attempted for two materials, steel projectiles on steel targets and aluminum on aluminum targets, and the results were fairly close to Bjork's theory. In determining these curves, the meteoroid diameter was equated to its mass through Figure 1. Also the thickness of the aluminum penetrated was assumed to be 1.5 times the penetration depth in a quasi-infinite aluminum plate, because of spalling effects. The aluminum was considered to be 6061-T6 alloy, with Brinnell hardness of 95 kg/mm^2. As seen, the empirical curve (Reference 10) corresponds well for stony meteoroids, and the Hughes maximum mass population with the curve of Reference 7, which is based on Bjork's theory, and the estimates of Kornhauser. Any of these curves should be suitable for conservative design criteria. The curves take into account only the sporadic meteoroid population, i.e., they do not include shower meteoroids. However, the curves themselves are conservative in that, in the range of interest, they are based on the Hughes maximum mass estimate of sporadic meteoroid population but there is evidence to suggest that, for these larger masses the actual population lies nearer the Watson estimate.

Figure 10 shows the penetrations that can be expected on a single solid aluminum sheet exposed in space. It is not likely that this condition will exist in an actual manned spacecraft, however. There will be additional structure between the pressure vessel (cabin) wall and the space environment, such as insulation, heat shield for re-entry, supporting structure, etc. Such structure will act as a meteoroid "bumper" and serve to protect the pressure vessel from puncture. Indeed, if such additional structure is not present, it would be advisable to add meteoroid bumper shields around the space cabin, for such action would result in a weight saving. In a laboratory test of the effect of hypervelocity projectiles on multi-walled space vehicles and missiles conducted by GE-MSD (Ref. 6), it was found that the use of a single shield resulted in a total weight saving of wall material of 50% or more. (That is, taking the relative weight of a single unshielded wall as 1, the addition of a single shield reduces the relative weight to 0.5 divided between shield and wall for the same wall penetration effects.) Shield thicknesses of 0.063 to 0.250 inch were used in the test. The shield serves to break up the incoming projectile, reducing the energy, and scatters the bits of projectile and shield over a wider area of the primary wall. Thus the total impact from the meteoroid on the pressure vessel wall would be reduced and the brunt of the impact would be taken over a wider area.

2.2.2 Hypervelocity Tests

Hypervelocity particle impact tests were conducted on representative manned re-entry vehicle structures to gain an insight into both the probability of cabin puncture and the nature of the puncture itself for repair purposes. Four tests were conducted, one for each test structure, and the results are shown in Figures 11 through 22. The test pieces consisted of 1/2 inch thick ablation material bonded to a 1 inch thick aluminum honeycomb substructure of about 6 inch diameter. Spaced 1 3/4 inches from the inside face of the honeycomb was an 0.040 aluminum plate, again 6 inches in diameter representing the pressure cabin. The ablation material was of the low density series, representative of the type proposed for future re-entry vehicles, and was cast into a phenolic fiberglass core. The aluminum honeycomb had a hexagonal cell core measuring 0.238 inch (between parallel sides) and weighing about 10-11 lbs/ft^3. The core was faced with 0.020 aluminum sheet.

The tests were conducted at GE-MSD hypervelocity impact test facility at Morgantown, Pa. The direction of particle impact was the same for all four test samples, normal incidence impact first striking the ablation shield, then penetrating the aluminum honeycomb substructure, and finally impacting the aluminum plate (cabin wall). The tests were conducted at atmospheric pressure; however, in the test fixture, there was a vacuum drawn between the aluminum honeycomb and the aluminum plate. The test parameters were as follows:

1. High velocity cylindrical aluminum particle, 1/8 inch dia., 1/8 inch long. Velocity 11,900 ft./sec. (Figures 11 through 13).

2. High velocity cylindrical aluminum particle, 1/4 inch dia., 1/4 inch long. Velocity 11,000 ft/sec. (Figures 14 through 16).

3. Same as No. 2. except velocity 11,500 ft./sec. (Figures 17 through 19).

4. Hypervelocity aluminum particles. Velocity 30,200 ft./sec. Total mass (approximately) between 0.5 and 1.4 grams. (Figures 20 through 22).

2.2.2.1 Results and Conclusions

In test number one, the impacting particle did not penetrate the aluminum plate (cabin wall) although it did penetrate the honeycomb. The impact on the simulated pressure cabin did raise a very slight dimple on the inside surface, however, which is not apparent in the photograph (Figure 13, circled area), but could be observed in the actual test piece.

In test number two, two rather large jagged punctures were created in the simulated pressure cabin skin, together with several smaller punctures. The larger major puncture measures about 3/4 inch long by 1/4 inch wide, and the other major puncture measures about 7/16 inch by 1/4 inch. There are 7 other smaller punctures and innumerable dimples in the plate also. The hole in the aluminum honeycomb measures about 1 1/2 inches diameter on the front face (bonded to the ablation shield) and about 2 inches diameter on the back face. The third test, which duplicated the second as far as test conditions, created one major puncture in the pressure cabin skin of about 1/4 inch diameter. In addition, there are three other smaller punctures, plus numerous dimples. Apparently, in this test, the impacting particle remained intact, and was not broken up to the same extent as in test #2. The hole in the honeycomb is smaller also, measuring 1 inch diameter on the front face and about 1 1/2 inch diameter on the rear face.

The fourth test utilized a hypervelocity jet projector which is capable of producing much higher velocities than those produced in the first three tests which used a mortar or "gun" type projector. However, the projected particle is not a coherent mass, or slug, but rather a long train of smaller particles. Thus, while the velocity more closely simulates that of meteoroids, the particle geometry does not. The hypervelocity jet projector is still under development and efforts are continuing to develop higher velocities and more coherent projectiles. The shot produced one large puncture in the simulated pressure cabin which measures about 1/2 inch by 1/4 inch and is oval in shape. The absence of dimples and other smaller punctures indicates that

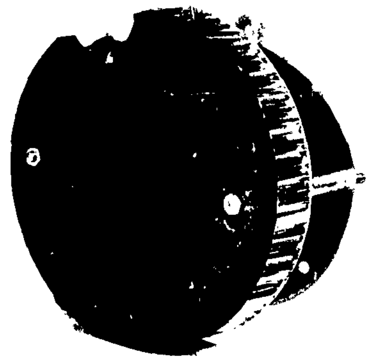


Figure 11. Hypervelocity Meteoroid Impact Damage - Thermal Shield (Test No. 1)

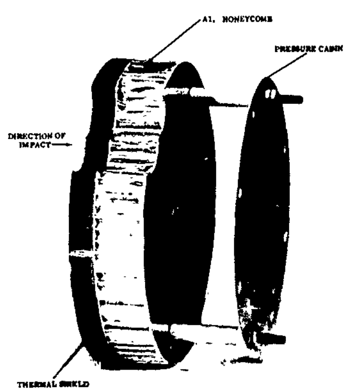


Figure 12. Hypervelocity Meteoroid Impact Damage - Backup Structure (Test No. 1)

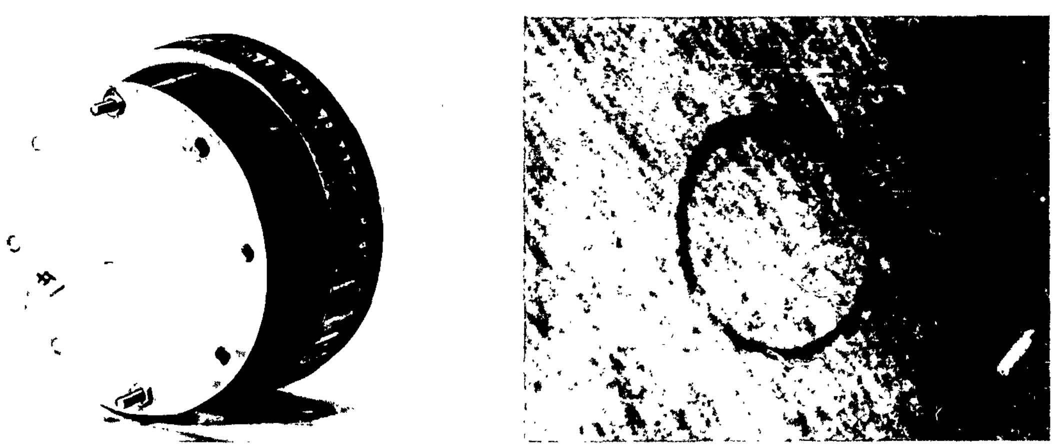


Figure 13. Hypervelocity Meteoroid Impact Damage - Pressure Cabin (Test No. 1)

Figure 14. Hypervelocity Meteoroid Impact Damage - Thermal Shield (Test No. 2)

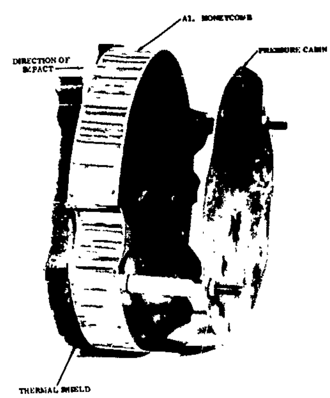


Figure 15. Hypervelocity Meteoroid Impact Damage - Backup Structure (Test No. 2)

Figure 16. Hypervelocity Meteoroid Impact Damage - Pressure Cabin (Test No. 2)

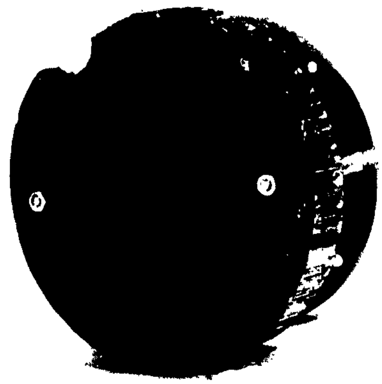


Figure 17. Hypervelocity Meteoroid Impact Damage - Thermal Shield (Test No. 3)

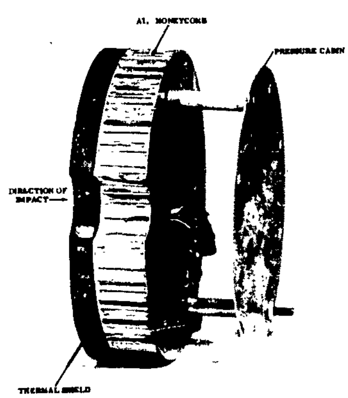


Figure 18. Hypervelocity Meteoroid Impact Damage - Backup Structure (Test No. 3)

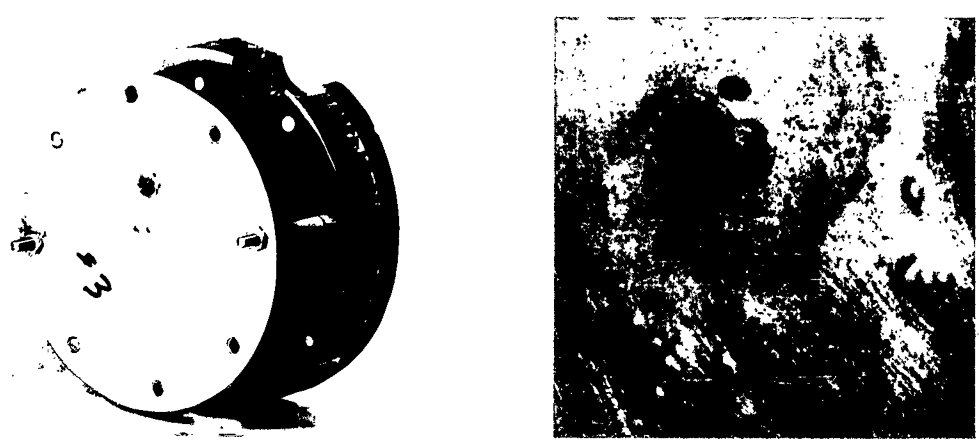


Figure 19. Hypervelocity Meteoroid Impact Damage - Pressure Cabin (Test No. 3)

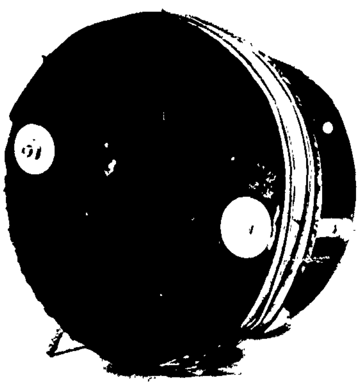


Figure 20. Hypervelocity Meteoroid Impact Damage - **Thermal Shield (Test No. 4)**

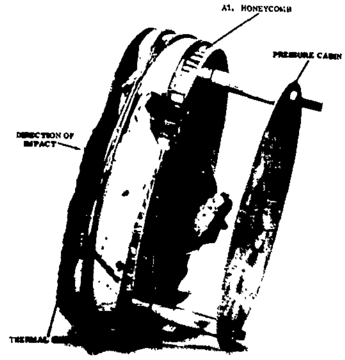


Figure 21. Hypervelocity Meteoroid Impact Damage - **Backup Structure (Test No. 4)**

Figure 22. Hypervelocity Meteoroid Impact Damage - **Pressure Cabin (Test No. 4)**

only one particle (or possibly many particles each traveling along the same path) impacted on the plate. The edges of the puncture, while raised and sharp, are not nearly as jagged as those in tests #2 and #3. The hole in the honeycomb measures about 5/8 inch diameter on both sides. The front face of the honeycomb gives evidence that more than one particle impacted, but only one penetrated. The mass of the particles was estimated, based on similar firings with aluminum. The estimate of mass is somewhere between 0.5 and 1.4 grams.

The results of these tests can be extrapolated using the empirical formulae of reference 10 for penetration, and the Hughes maximum mass meteoroid population curve. When this is done, the probability of sustaining impacts such as witnessed by the four test samples can be calculated with the following results (based on stony meteoroids).

Test #1. Equivalent meteoroid mass = 2.5×10^{-3} gms.
velocity = 40 km/sec
P = 3.2×10^{-4} impacts/100ft^2/day

Test #2 & 3.

Equivalent meteoroid mass = 1.8×10^{-2} gms
velocity = 40 km/sec
P = 1.4×10^{-5} impacts/100ft^2/day

Test #4.

Equivalent meteoroid mass (based on assumed 1 gm mass for test projectile) = 2×10^{-1} gms
velocity = 40 km/sec
P = 3.6×10^{-6} impacts/100 ft^2/day

Since the particle of test #1 did not penetrate the cabin, the probability of puncture for this representative structure is below 3.2×10^{-4} impacts/100 ft^2/day but certainly above 1.4×10^{-5} impacts/100 ft^2/day. A realistic value would be on the order of 1×10^{-4} impacts/100 ft^2/day. Thus for a 1000 ft^2 surface area cabin of this construction, penetration would occur approximately 1×10^{-3} per day, or one penetration every 1000 days.

2.2.3 Meteoroid Risk

The specific danger, then, to any particular spacecraft depends on the detail design of the wall structure of the vehicle. Recent studies of manned space vehicles conducted by GE-MSD have included an analysis of the meteoritic risk to the inhabitants, based primarily on the information given in the preceding discussions. The results of these analyses for four different manned vehicle studies are as follows:

The first study concerned an Apollo type vehicle which consisted of a command module housing the crew of three, the service module housing the in-flight propulsion system and an adapter section connecting the two. The service module and adapter external shell structures were sized to limit meteoroid penetration of the shell to a probability of 0.001 to achieve the required mission reliability. This requirement was more critical for design of the structure than were the loading requirements. Accordingly, honeycomb sandwich construction was introduced to provide the maximum effectiveness against penetration. The service module requires effective meteoroid protection because normal or emergency return propulsion is essential while access to components for in-flight repair was considered restricted.

For the command module, there are two primary modes of failure — penetration of the pressurized cabin and re-entry heat shield degradation. The module consists of an ablation heat shield bonded to an aluminum honeycomb substructure separated by a gap from the welded aluminum sheet pressure cabin. The heat shield-honeycomb outer structure then acts as a meteoroid bumper protecting the pressure vessel wall. The probability of pressure cabin penetration was calculated to be 0.00386. However, any penetration of the shield substructure inner wall results in failure at re-entry due to the internal hot-gas flow from the external boundary layer. Therefore, it is imperative that the capability for in-flight inspection and repair of the heat shield prior to re-entry be included in the mission.

The vehicle design resulting from the second study program under consideration is shown in Figure 23. The vehicle consists of three modules — the mission module, propulsion system, and re-entry vehicle module. The structure of the propulsion and mission modules is similar to the re-entry vehicle shown except the thermal shield and aluminum skin (middle bumper) are deleted. The probability of meteoroid puncture was analyzed by two methods. The first method was developed by M. Kornhauser, GE-MSD (Ref. 2) and assumes a meteoroid population equivalent to the Hughes maximum mass data. The second method, by D. Beard (Ref. 3) is based on an average meteoroid population. The results of these analyses illustrate the variations in damage predictions and the necessity for careful consideration of meteoroid damage in spacecraft design.

The results tabulated in Figure 23 reflect the "bumper" effect of the spacecraft outer shell structure in protecting the internal components by shattering small meteoroids penetrating the shell. The Kornhauser method indicates the spacecraft outer shell would be penetrated by meteoroids 21 times in 14 days (i.e., 21 times/mission). The re-entry vehicle pressure cabin, protected by multiple bumpers (spacecraft outer shell and re-entry vehicle structure) would receive one penetration in 640 missions. In addition, the mission module would be penetrated once in 6 missions, and the propulsion module once every 30 missions. Local bumpers (a good use for beryllium) could further reduce meteoroid damage of these modules.

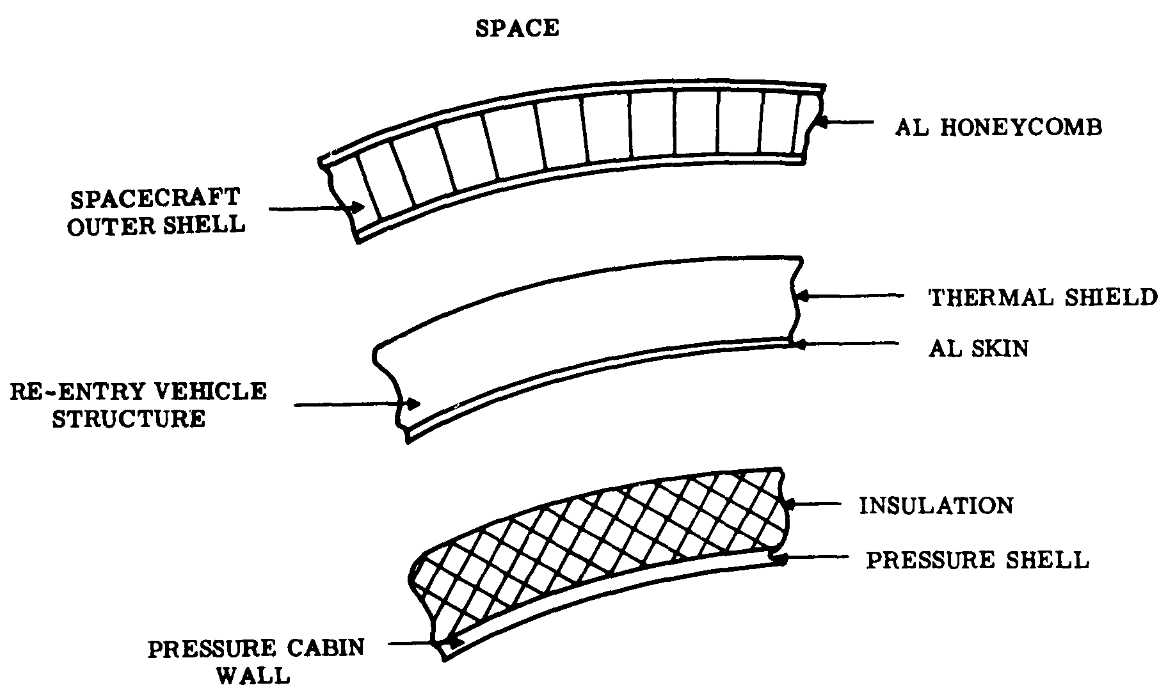


Figure 23. Typical Bumper Protection for Re-entry Vehicle Pressure Cabin (Sectional View)

Penetrations/Mission

Vehicle Area \ Method	Kornhauser (Ref. 2)	Beard (Ref. 3)
Spacecraft Outer Shell	21	7
Mission Module	1/6	1/50
Propulsion System	1/30	1/500
Re-entry Vehicle Pressure Cabin	1/640	1/26,000

The more optimistic, but not necessarily more valid, method of Beard gave 7 penetrations of the outer shell per mission and one penetration in 26, 000 missions for the re-entry vehicle cabin. Results of this method also indicate the mission module and propulsion system would receive one penetration in 50 missions and one penetration in 500 missions, respectively.

The study recommends that the method of M. Kornhauser be specified for assessing the effects of meteoroid impact in this vehicle. This method, although seemingly conservative, appears justified for design pending a great deal of further flight test data and added experimental confirmation of theory. An estimate of the penetration hole size for the re-entry vehicle pressure cabin is approximately one inch in diameter and serves to emphasize the necessity for access to the cabin inner surface for repair.

The above results were based on a rational assessment of the effect of bumpers in alleviating meteoritic damage based on tests conducted at GE-MSD (Ref. 6).

In the third study which concerns a larger, longer duration, manned space vehicle, the penetration effects of meteorite impact were determined by using, generally, the Kornhauser method (Ref. 2). The vehicle shell thickness required was calculated for various penetration frequencies. This is shown in Figure 24 for the manned portions of the entire fuselage, the forward capsule, and crew. Since this particular vehicle was designed for a low earth orbit mission, the surface area of each item was divided by two, assuming that the earth shields the bottom half of the the vehicle. (This would not be true, of course, if the vehicle were designed for interplanetary or high orbit missions, in which case the penetration frequencies shown in Figure 24 would double.)

The criteria used to determine the meteoroid shielding requirements were based on the allowable penetration probability for a crew member. Obviously, there are many medical and human factors involved in the question of the type of injury suffered by such a penetration, but, for simplification, it was assumed that penetration of a crew member would result in death. A reasonable death rate was then determined to be between .6 and 2.0 deaths per million man-hours (corresponding to the death rates for automobile passengers and airline passengers, respectively). For this vehicle, these levels are equivalent to one death per 280 and 83 missions, respectively.

Referring to Figure 24, it appears that the required wall thicknesses are as follows:

Death rate per 10^6 man-hours	Missions/death	Wall thickness Unshielded (inches)	Wall thickness Shielded (inches)
.6	280	.60	.30
2.0	83	.40	.20

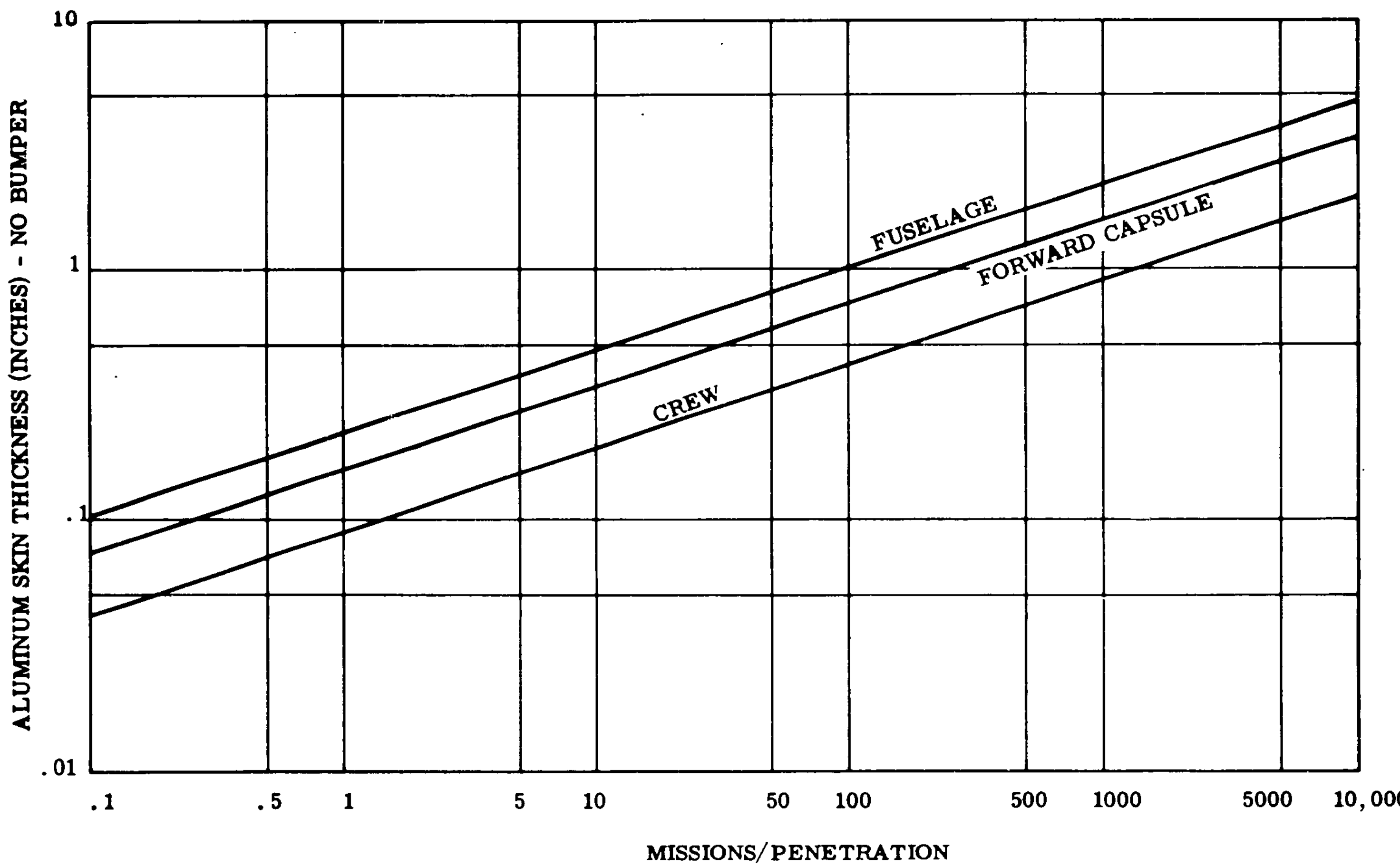


Figure 24. Wall Thicknesses Required for Various Penetration Frequencies

A reasonable distribution of the time spent by the crew in the various compartments of the vehicle is tabulated below. The thickness of various shell materials required to protect the crew (based on a death rate of 2.0 per million man-hours) is also shown as well as the number of penetrations per mission.

Area	Man-hours (percent)	Shielded Thickness Required			Missions per penetration
		Aluminum	Beryllium	Phenolic Nylon	
Command Forward	78	.20	.14	.23	16
Recreation Area	17	.12	.09	.14	4
Equipment Area	5	.08	.06	.10	.5

Note that it is evident that several penetrations of the vehicle can be expected per mission. The wall thickness requirements were based on the penetration probability of a crew member because it was assumed that penetration of the shell, with the resultant loss of pressure integrity, and equipment damage would not be catastrophic. That is, the capability for repair of leaks and repair of equipment is required for the vehicle mission.

The meteoroid penetration analysis for the MTSS vehicle,the fourth study,is similar to the above. The shielding requirement is, again, based on 2 deaths per million man-hours (equivalent to airline passenger) from meteoroid penetration. It was determined that one in 29 penetrations could be considered dangerous (i. e., fatal to one of the crew). Based on this figure the MTSS vehicle could reasonably tolerate 28 penetrations per 500, 000 man-hours or 83, 300 flight hours.

The required thickness of aluminum to restrict the number of penetrations to this amount is 0.43 inches. For a double wall (i. e., "bumper") the required thickness can be reduced to 0.22 inches divided between the bumper and pressure skin. The radiation protection compartment built into the vehicle, surrounded by 1.375 inches of aluminum, is inherently protected and can be considered an "island of safety" where penetration will occur once every 220 years.

It is evident from the above that penetration of the spacecraft will occur about once every 3000 hours. When this occurs, provisions for repair of the vehicle and damaged equipment must be provided.

2.3 VACUUM

The range of gas pressures found in space is shown in Figure 25. The pressure falls with altitude from about 10^3 mm Hg at sea level to 10^{-6} mm Hg at 125 miles. Above 4000 miles altitude, the pressure is less than 10^{-12} mm Hg; and in interplanetary space, the pressure is thought to be 10^{-16} mm Hg, which corresponds to a density of 4 molecules/cc. Compared with laboratory vacuum systems, 10^{-6} mm Hg can be obtained with good equipment and 10^{-13} mm Hg is about the best vacuum ever attained in the laboratory.

One of the main effects of space vacuum on materials is the loss of material by evaporation or sublimation. The rate at which materials are lost to the space vacuum is given by the Langmuir equation

$$W = \frac{P}{17.14}\sqrt{\frac{M}{T}} \quad \text{where}$$

W = rate of evaporation or sublimation - gms/cm^2 - sec

P = vapor pressure of the material - mm Hg

M = molecular weight of the material in the gas phase

T = temperature, K

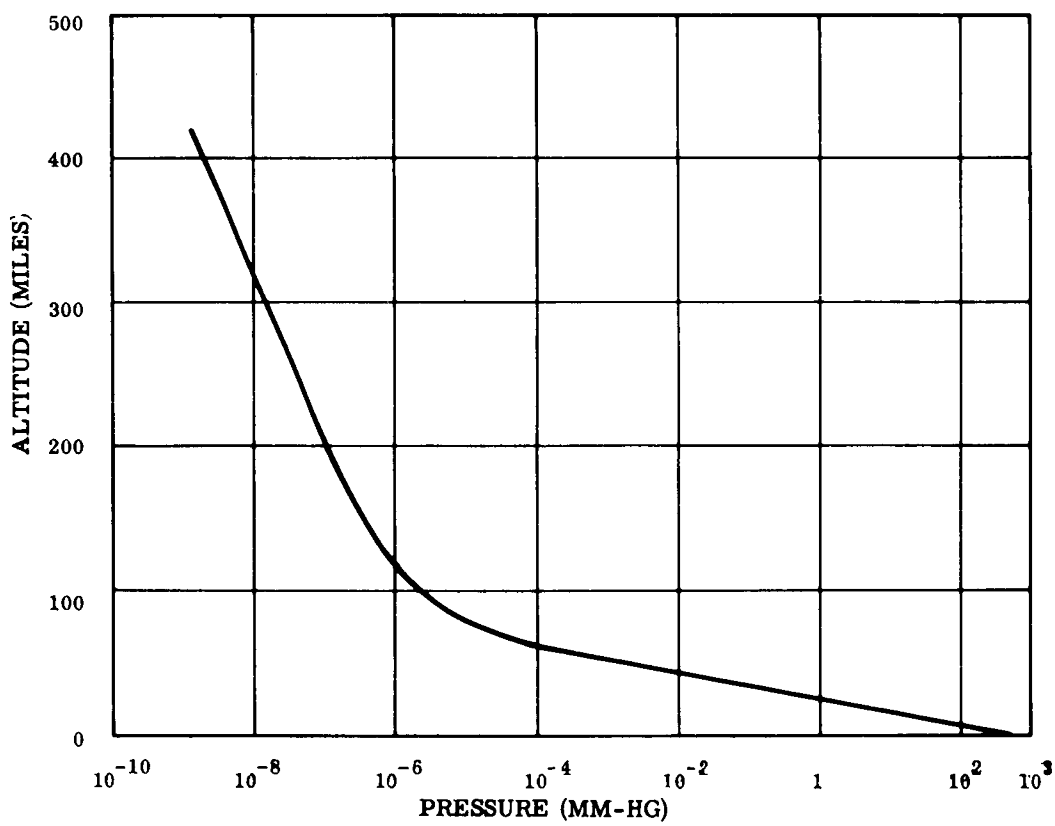


Figure 25. Pressure vs. Altitude Above Earth

It should be noted that W will increase with increasing temperature even though $\sqrt{T}$ is in the denominator of the equation because P increases rapidly with temperature.

For most elements and inorganic materials, the vapor pressure is known and the loss of material can be calculated from the above equation. Table 4 lists losses that can be expected for many materials of interest (Ref. 7).

TABLE 4. SUBLIMATION OF METALS AND SEMICONDUCTORS IN HIGH VACUUM

	Temperature at Which Given Sublimation Rate Occurs			
Element	10^{-5} cm/yr (1000 Å/yr) (°F)	10^{-3} cm/yr (.0004 in/yr) (°F)	10^{-1} cm/yr (.040 in/yr) (°F)	Melting Point (°F)
Cd	100	170	250	610
Se	120	180	240	420
Zn	160	260	350	790
Mg	230	340	470	1200
Te	260	350	430	840
Li	300	410	530	360
Sb	410	520	570	1170
Bi	470	600	750	520
Pb	510	630	800	620
In	760	940	1130	310
Mn	840	1010	1200	2270
Ag	890	1090	1300	1760
Sn	1020	1220	1480	450
Al	1020	1260	1490	1220
Be	1140	1300	1540	2330
Cu	1160	1400	1650	1980
Av	1220	1480	1750	1940
Ge	1220	1480	1750	1720
Cr	1380	1600	1840	3410
Fe	1420	1650	1920	2800
Si	1450	1690	1970	2570
Ni	1480	1720	2000	2650
Pd	1490	1720	2020	2830
Co	1500	1760	2020	2720
Ti	1690	1960	2280	3040
V	1870	2150	2460	3450
Rh	2080	2420	2800	3570
Pt	2120	2440	2840	3220
B	2240	2580	2980	3700
Zr	2340	2740	3150	3360
Ir	2380	2740	3150	4450
Mo	2520	2960	3450	4730
C	2780	3050	3400	6700
Ta	3250	3700	4200	5400
Re	3300	3700	4200	5800
W	3400	3900	4500	6200

It appears highly unlikely that evaporation or sublimation of metals in a vacuum, used as structure in a space vehicle, would cause leaks in the pressure cabin. First, this process would not form holes in the material for the following reason: although the evaporation is selective toward individual grains, metal sheets are many grains thick and this selective process would be averaged out along the surface. The chief result would be the roughening of the surface on a microscopic scale. Second, the reduction in thickness of the metal is predictable. Thus any loss of strength of the structure resulting from this loss of material can be accounted for in the design of the vehicle. It is possible that the microscopic roughening of the surface may lower the fatigue life of the structure (because of a notching effect) but this has not been determined. In addition, there is no evidence of a loss in the structural properties of metals due to vacuum.

In the case of organic materials, evaporation and sublimation cannot be predicted by the Langmuir equation. This is because most organic materials planned for use in spacecraft are long chain polymeric compounds whose degradation in vacuum is due to the breakdown of the compound into smaller, volatile components. The composition of these components, as well as the pressure at which the breakdown occurs, is not well known, and therefore the behavior of these compounds must be determined through testing.

Perhaps the most significant parameter in evaluating the vacuum effects on organic materials is the percentage of weight lost by the test sample as a result of exposure to vacuum. In general, a weight loss of 10% indicates that significant properties (i. e., brittleness, strength, hardness, etc.) of the material have changed. On the other hand, a weight loss of only 2% is not significant, and the material properties are unchanged. Of prime importance also is the time required for significant weight loss to occur. In general, a plot of time versus weight loss is not linear, thereby creating some difficulty in extrapolating short duration tests to long duration estimates. The best approach to use in extrapolating appears to be the assumption that a plot of log time vs. 1/T is linear. Data for several materials extrapolated in this manner is given in Table 5 below (taken from Ref. 7).

TABLE 5. DECOMPOSITION OF POLYMERS IN HIGH VACUUM ($p = 1 \times 10^{-6}$ mm Hg)

POLYMER	TEMPERATURE FOR 10% WT. LOSS/YR (^{o}F)
Nylon	80 - 410
Methyl acrylate	100 - 300
Vinyl chloride	190
Methyl methacrylate	220 - 390
Acrylonitrile	240

TABLE 5. (Cont'd)

POLYMER	TEMPERATURE FOR 10% WT. LOSS/YR (^oF)
Styrene	270 - 420
Cellulose	350
Methyl styrene	350 - 420
Cellulose acetate	370
Propylene	370 - 470
Ethylene terephthalate (mylar, dacron)	400
Styrene, cross linked	440 - 490
Ethylene, low density	460 - 540
Chlorotrifluoroethylene	490
Vinylidene fluoride	510
Ethylene, high density	560
Trivinyl benzene	560
Tetrafluoroethylene	710

The chief interest, from the standpoint of leakage, will be the effect of vacuum on the elastomeric materials used for seals in the space cabin. It is possible that progressive degradation of these organic materials could cause property changes that would create leaks. An example of the type of failure that can occur is given in Table 6 (Ref. 8).

TABLE 6. POSSIBLE TYPES OF FAILURES THAT CAN OCCUR DUE TO ORGANIC MATERIAL DEGRADATION

Compound No.	Pressure (mm Hg)	Weight Loss	Leakage cc air/inch of seal/year
B 318-7 (Butyl base)	1×10^{-7}	2.0%	
	1×10^{-8}	31.0%	
	2.2×10^{-7}		0.0011
	2.2×10^{-8}		1.2200

In this test, the butyl rubber compound seal was subjected to vacuum for six days at room temperature. As shown, performance at a pressure of 1×10^{-7} mm Hg was satisfactory. However, at an order of magnitude lower pressure, the weight loss was excessive as the leakage rose to about 1000 times the previous value. Examination of the seal after exposure to 1×10^{-8} mm Hg revealed erosion of the outer surface of the material. In another test, a viton synthetic rubber compound successfully sealed against a vacuum of 2×10^{-9} mm Hg. The same compound exposed to 1.8×10^{-9} mm Hg for 144 hours experienced a weight loss of only 2% (at room temperature).

The above information points out that the selection of elastomeric seals for very high vacuums such as found in space, depends on material development through adequate testing. Laboratory testing below 1 x 10^{-9} mm Hg is limited, however, as well as testing for long durations. It is difficult to predict the state-of-the-art for seals for the future as the altitude of spacecrafts increase and the mission duration becomes longer.

Perhaps seals for these future space vehicles will have been adequately tested in the laboratory or in unmanned satellites, so as to insure their resistance to vacuum erosion. Or, they could be selected on engineering estimates and extrapolations which would leave a small chance for error and failure. It is conceivable too, at this point, to conjecture that seals, as an example, for a space station orbiting at 22,000 miles altitude with a life span of five or ten years, will have to be periodically inspected, repaired and/or replaced.

2.4 STRUCTURAL FAILURE

There are several other hazards associated with space flight, not directly dependent on the space environment, that could cause leaks in the seals or structure of a space cabin. The effects of these hazards are not readily predictable and thus it is difficult to assign a probability factor to them. The likelihood of these hazards occurring is small; nevertheless, the likelihood exists and the crew should be protected, within reason, from the damage and leakage resulting from these failures. These hazards can be categorized as follows:

a. Stress of Launch, Boost and In-flight Maneuvers, etc. - The action resulting from launch, boost and in-flight maneuvers produces stresses on the vehicle structure. These accelerations and vibrations are predictable and the spacecraft can be tested during development and qualification to demonstrate its reliability to sustain these stresses plus an additional safety factor. There remains a possibility of a propulsion system failure, however, which could produce greater than ultimate stresses in some portion of the spacecraft, thus opening up a seam or cracking a seal, etc. If this happens near the earth, it should not be critical from a leakage standpoint since the crew, utilizing suitable secondary pressure protection, can return the vehicle to earth in a relatively short time. However, if the failure occurs far from earth - for example, in landing or taking off from the moon or another planet - repair of the damage and leaks will be required. A possible exception to this would be if the crew could use secondary pressure protection until the craft could be brought to earth.

b. Vibrations From Equipment - It is conceivable that other equipment besides the propulsion system may fail or become dynamically unbalanced so as to cause additional stresses on the

vehicle. These stresses would be vibratory in nature, and if of sufficient strength to develop fatigue cracks in the cabin wall, would create additional leakage.

c. Internal Fire or Explosion - The results of a fire or explosion aboard a spacecraft could range from minor damage to catastrophic failure of the vehicle. Leaks caused by fire could result from degradation of seals and/or weakening of the structural material. Explosions could develop cracks or open up seams in the pressure cabin, or distort seal surfaces. The requirement for repair of the leakage thus created depends on the time required for the vehicle to return to earth and the capability of the secondary pressure protection system for the men.

d. Collision During Rendezvous - There are many missions that could be contemplated which involve rendezvous in space with other man-made objects. The manned space vehicle could rendezvous with a space station, another spaceship, unmanned satellites, refueling stations, etc. Such operations require extreme precision in alignment of speed, direction and proximity. It is conceivable that collisions could and may occur, resulting in failure of the pressure integrity of the manned vehicle or vehicles.

e. Hostile Action - The space vehicle could be subjected to hostile action, particularly if it is a military vehicle on a military mission. Such action could involve the detonation of a nuclear device in close proximity to the spacecraft. Because of the absence of blast effect in space, the primary destructive forces would be thermal and nuclear radiation. Providing the crew and vehicle survive the detonation fairly intact, the resultant leakage should be similar to that caused by an internal fire (i.e., degradation of the seals and/or weakening of the structure).

It has been speculated that another type of hostile action would be to fire a multitude of high energy projectiles at the vehicle. In this case, the effects on the vehicle could be similar to meteoroid puncture.

f. Random Design Failure - Unless the reliability of cabin pressure integrity is 1.00, which is highly unlikely, there will always be the chance of a random failure occurring. While this chance will be admittedly low, protection of the crew from the results of such failure provides an extra margin of insurance.

III. REQUIREMENTS

3.1 INTRODUCTION

As we have seen in the preceding section, there are many real dangers in space flight which could disrupt the pressure integrity of the space cabin. Excessive loss of cabin atmosphere resulting from these leaks would have the detrimental effect of either causing an abort of the mission (i.e., return to earth) or loss of the crew. To prevent these most costly effects, the crew can be provided with a means of repairing cabin leaks and thus return the cabin to its original usefulness. Of course, prior to repairing a leak, the leak must first be detected, and then located. The following section discusses the requirements for such a leak detection, location and repair system.

3.2 REQUIREMENTS FOR THE LEAK DETECTION, LOCATION AND REPAIR SYSTEM

3.2.1 Minimum Detectable Leak

It should be recognized that every future manned space vehicle will exhibit some leakage which cannot be eliminated within reasonable size and weight penalties. The majority of this leakage will occur around the many seals required in the pressure cabin. These seals will have to be used for all items, services, portholes, hatches, etc., which penetrate and break the continuity of the pressure cabin skin. In a properly designed hard vacuum seal using an elastomeric o-ring, or gasket, leakage will occur through permeation of the gas through the elastomer. In this process, the gas enters into solution with the polymer substance of the seal, diffuses across the seal, and evaporates to the vacuum. The rate of permeation, with typical units, is given by the following equation:

$$Q = \frac{PA\Delta P}{\delta}$$

Q = gas permeating (cc/sec)

P = permeability coefficient of the seal for the particular gas $\frac{(\text{cc-cm} \qquad)}{(\text{sec-cm}^2\text{-cm Hg})}$

A = cross sectional area of seal (cm^2)

ΔP = partial pressure difference of gas across seal (cm Hg)

δ = thickness of seal (cm)

The rate of gas leakage from any particular seal depends then on the geometry and material used. Typical values for this permeability leakage are from 0.01 to 1.0 cc/year/linear inch of seal. Note that

in this type of seal leakage, the concept of leakage through small orifices is absent. This is true if the seal maintains an unbroken line of contact with the seal surfaces. Any break in this line, due to stresses, etc. will increase the leakage considerably by allowing flow around the seal. It may not be feasible, within present weight allowances, to eliminate this latter type of leakage completely so that the total inherent leakage from the capsule may be higher than that due to permeability alone.

This inherent leakage will be called "normal leakage" and provisions for extra gas supplies will have to be made to accommodate this. The amount of normal leakage will vary for different designs. The specification leak rate for Mercury is 300 STP cc/min. In a study of an Apollo type 3 man vehicle, the leak rate was projected as 1000 cc/min at 7.0 psia cabin pressure. In other studies, leak rates of 1500 cc/min for a 30 day space station and 3000 cc/min for a 1 year space station were assumed, both at cabin pressures of 7.0 psia. The predicted leak rate for these and other studies can be roughly approximated as about 500 cc/min/man at 7.0 psia. These leak rates were determined by extrapolating results from Mercury and assuming a reasonable advance in the state-of-the-art of sealing techniques for the time period in which the vehicles would be manufactured.

The leak detection system will not be required to detect this normal, inherent leakage, for if this leakage could be reduced, it would have been done prior to flight. What the leak detector must detect is leakage above the normal amount. For example, using the Apollo type vehicle study above as a typical future manned space vehicle, if the leak detector system is a type that responds to the total leakage, as in a pN_2 decay system, the minimum leak rate required to detect would be 1000 cc/min. If the leak detector system employs area type sensors (i.e., each sensor responds to leakage from a particular area of the cabin) the minimum detectable leak rate will have to be much less. For example, if 10 sensors are employed, each covering 1/10 of the total area, the minimum leak required for detection would be on the order of 100 cc/min. This would vary somewhat as not all areas would be expected to yield the same amount of normal leakage, so the minimum leak rate for one particular area could be reduced to perhaps 25 cc/min.

The minimum leak rate which the system must be capable of detecting, locating and repairing is then a function of the number of detectors employed, and the inherent vehicle leakage corresponding to each detector.

The above discussion relates the sensitivity required from the leak detectors to the leakage emanating from the entire vehicle, per se. In terms of an individual leak, resulting from a penetration of failed part, the minimum detectable leak must be much less. Figure 26 shows the leakage as a function of the diameter of an orifice through

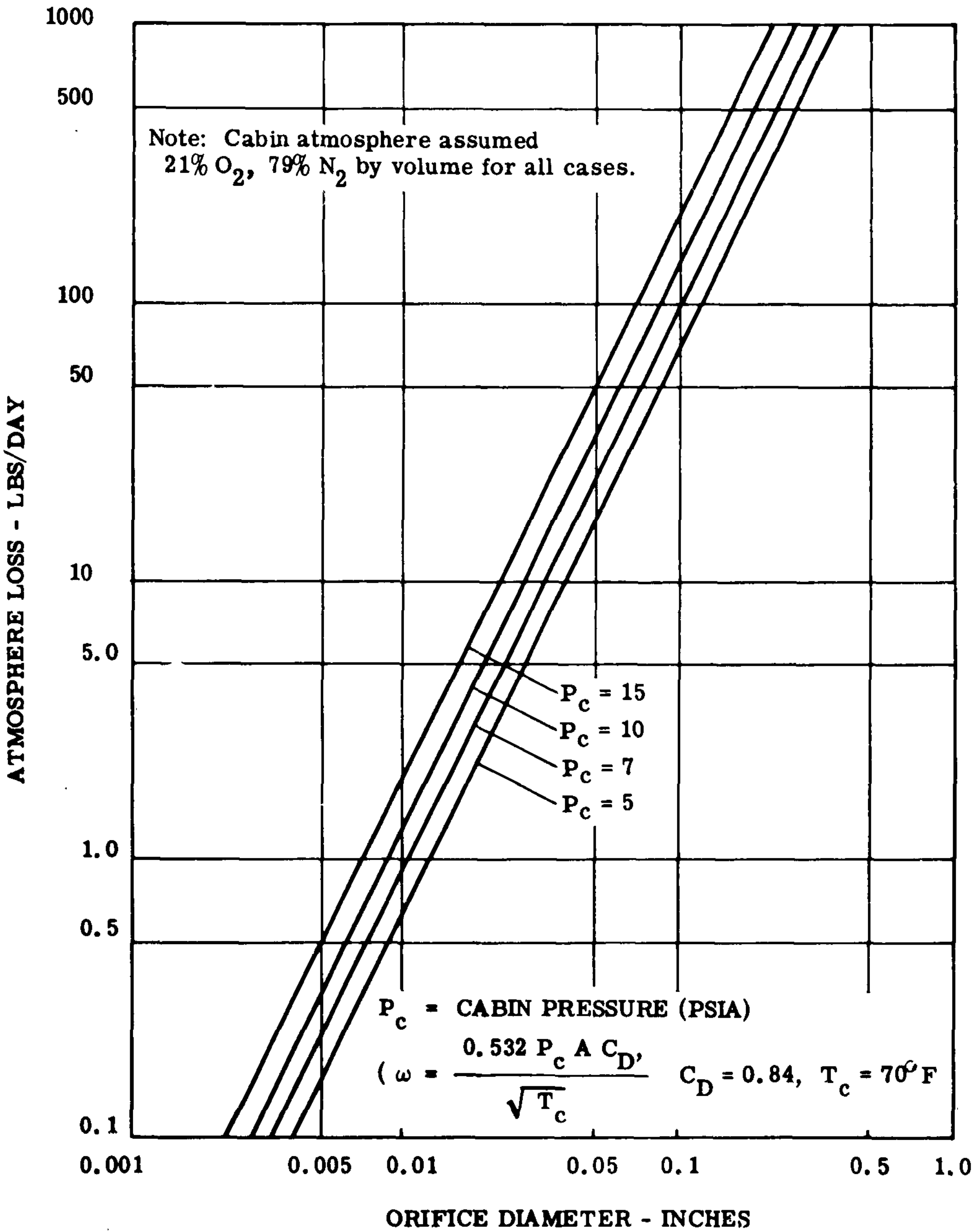


Figure 26. Cabin Atmosphere Loss Vs. Hole Diameter

the pressure cabin wall for various cabin pressures. As seen, some fairly large leakage results from small holes. (Note that the curves are based on standard air composition, 21% O_2, 79% N_2 by volume. Thus, the curves for the lower cabin pressures, which would have a higher O_2/N_2 ratio, are approximate; however, the error introduced is small.) The leak detector system must detect the smallest possible leak, while still remaining within the weight trade-off (see requirement for weight below). The equivalent hole size for the minimum leaks which must be detected, located and repaired ranges then from 0.005 inch to 0.010 inch dia. It is anticipated that locating holes and/or cracks of this small area will be more difficult than detecting their presence.

3.2.2 Maximum Repairable Leak

As the minimum size leak places the greatest burden on the detection and location system, the larger leaks place the greatest requirements on the repair system. As the magnitude of the pressure cabin penetrations increases, a point will be reached where the primary damage will be structural, and leakage will be of secondary importance. That is, the structural soundness of the vehicle has been impaired to such a degree that it is not able to withstand the loads imposed by the mission maneuvers or cabin pressure. If the crew survived such a major impact or rapid decompression, repair would be a major task requiring beams, stringers, plates, etc., plus welding or riveting equipment. This study will not be too concerned with leak repair of this type, except to say the repair has to be made leaktight as well as structurally sound.

For indications of the larger size holes that will have to be considered, however, reference will again be made to the meteoroid impact parameters. It is desirable to relate the size of the hole to the size of the impacting meteoroid. Unfortunately, this is not easily accomplished for the following reasons: One, referring to the sketch of Figure 27, the meteoroid upon impacting the "bumper" will shatter, and the fragments of meteoroid particles and bumper material will scatter through some conic angle, x, before impacting the pressure shell. The area of the pressure shell covered by the particles will depend on such factors as bumper to wall spacing, bumper material and thickness, etc. If the original meteoroid was very large, a majority of the particles created by bumper impact may have sufficient energy to penetrate the cabin wall, creating a hole several times larger in radius than the meteoroid. If smaller, however, only one or a few particles may penetrate the cabin shell, creating relatively small holes. As a base line an estimate of hole sizes created by meteoroids can be made by assuming the radius of the hole is equal to the equivalent radius of the impacting meteoroid. By using this estimate hole sizes of 0.1 inch and up radius can be expected with the probability decreasing as the size increases. Figure 28 shows probability of hole size formation for the larger size meteoroids of interest, and assuming the meteoroid can penetrate the cabin pressure skin.

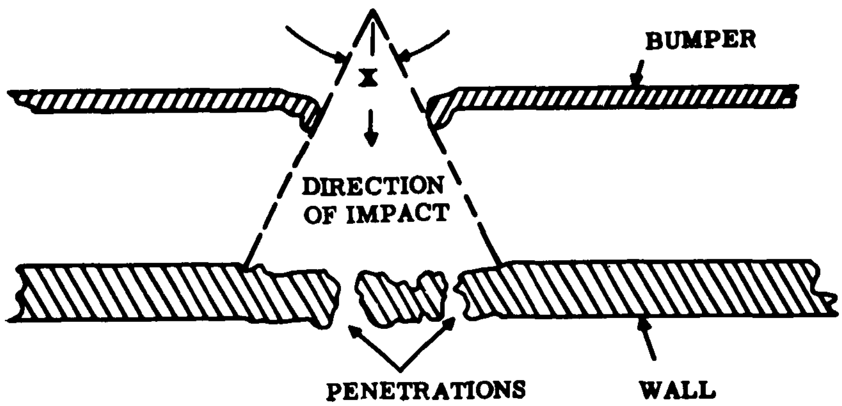


Figure 27. Meteoroid Shatter Geometry

3.2.3 Weight, Volume and Power

As with any other missile or spacecraft system, the weight, volume and power requirements are important factors which must be minimized in the overall system trade-offs. Also, power can be equated to weight and volume depending on the particular vehicle, i.e., power generating system utilized. This can be expressed as lbs/KW or ft^3/KW. Of the two remaining factors, weight and volume, weight is expected to be the most critical and volume of secondary importance. This will be true as long as the volume requirements are not abnormally high.

Weight can be directly compared with the leak rate and mission duration. The weight of the leak detection, location and repair system will also influence the minimum leak which must be detected for any particular mission duration. This effect is shown in Figure 29. Curve WL #1 represents the weight factor for leakage loss vs. leak rate for a particular mission duration. (Note: the leakage referred to stems from extraneous causes and is over and above the normal leakage which will be inherent in the vehicle.) Curve WL #2 represents the same thing except for a longer duration mission. The curves labeled System #1 and System #2 represent the weight of two different leak detection, location and repair systems versus the minimum leak rate they are required to detect. The System #1 curve intersects curve WL #1 at point A corresponding to a leak rate of ω_1 and a system weight of W_1. This is the trade-off point for this system and particular mission. This means that it would not be desirable to detect leakage of less than ω_1, because the weight of the system required to detect and repair this leakage would be greater than the leakage itself, if allowed to continue undetected and unrepaired. The same can be said for System #2 and mission WL #2 at point C. From a weight standpoint, it can be seen that System #1 is optimum for mission WL #1 and System #2 is optimum for mission WL #2

The above illustration is hypothetical but it does serve to illustrate that the minimum weight system may depend on the particular vehicle.

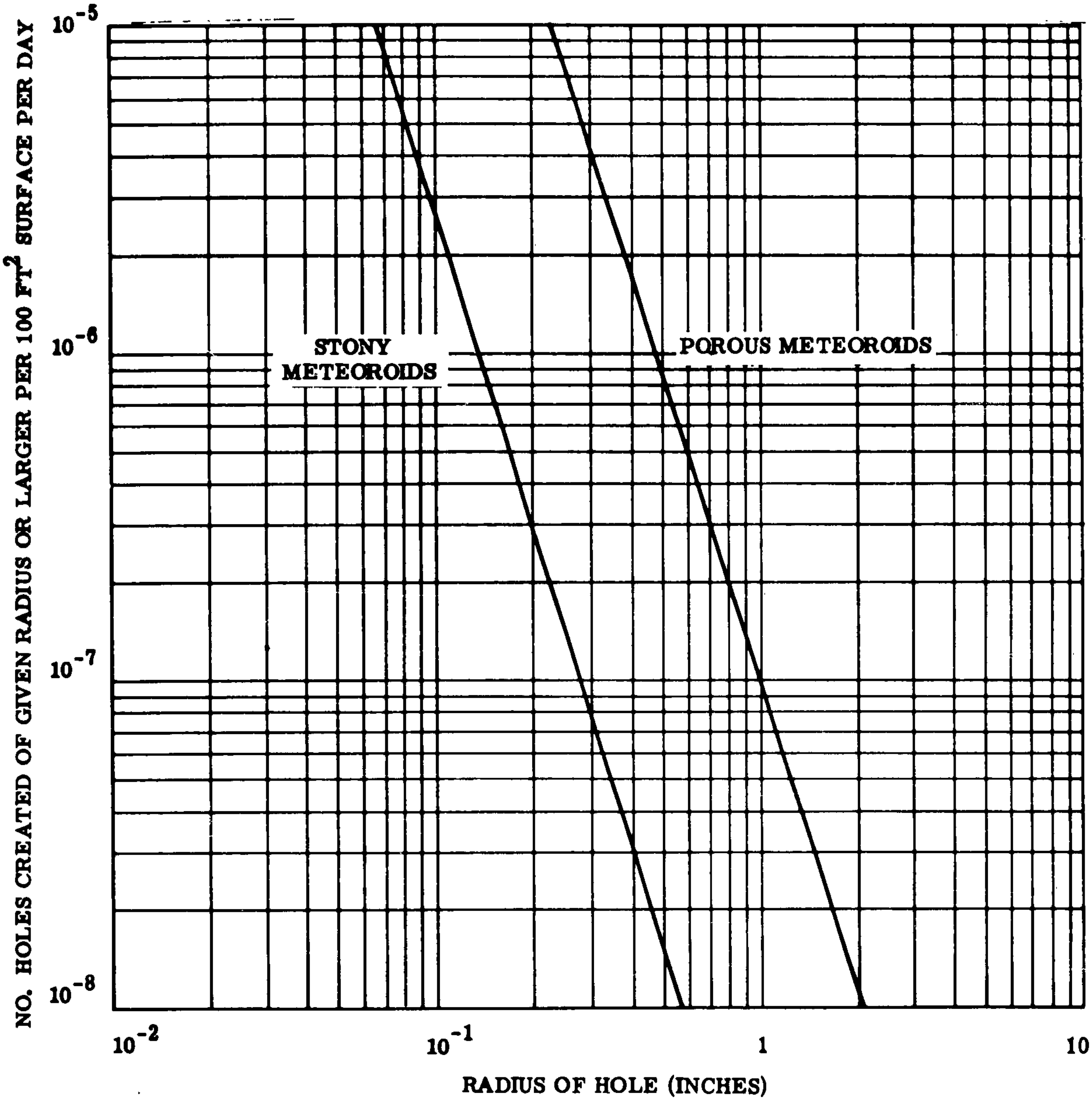
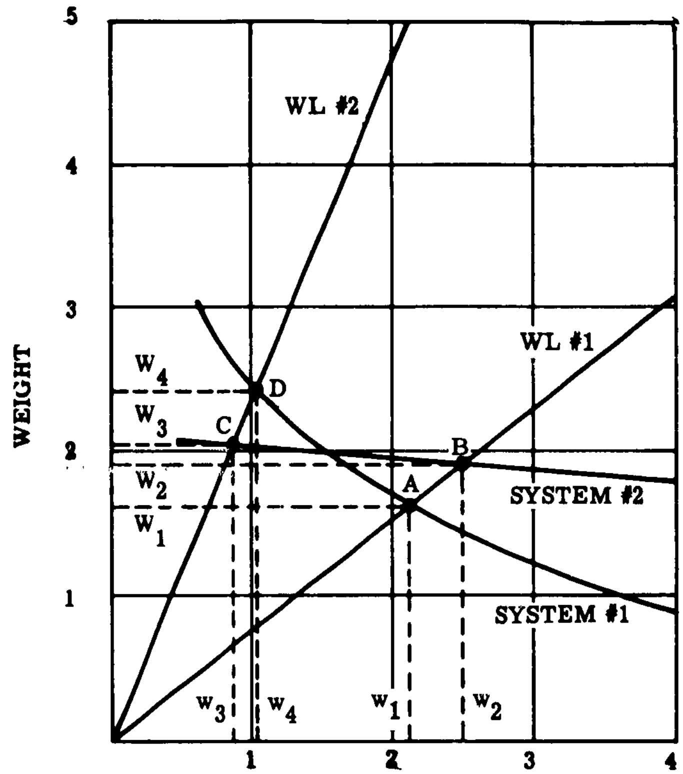


Figure 28. Probability of Hole Size Formation for Larger Meteoroids



WL #1 = leakage wt. penalty - short mission
WL #2 = leakage wt. penalty - long mission
A, B, C, D = trade-off points
w_1, w_2, w_3, w_4 = minimum detectable leak @ pts A, B, C, D resp.
W_1, W_2, W_3, W_4 = system wt. @ pts A, B, C, D resp.

Figure 29. Weight Parameters, Hypothetical Case, Arbitrary Units

This is further amplified when different power systems are used, for this could greatly effect the equivalent system weight for the leak detection, location and repair system.

3.2.4 Time for Detection, Location and Repair

The time from the initiation of a leak to its eventual repair should be as short as possible in order to minimize the amount of leakage lost. The weight of the lost atmospheric gases can be added to the equivalent weight factor of a leak detection, location and repair system for any particular leak rate. The amount of gases lost will be a direct function of the size of the leak, as well as the time required for repair. Therefore, it becomes more imperative to repair the larger leaks quickly while more time may be allowed for repair of smaller leaks.

For the larger leaks of 0.1 inch equivalent diameter or larger, it may be desirable to allow the cabin to decompress rather than maintain a constant cabin pressure. Considerable gas supplies may be saved in this way, as the leakage through the orifice is directly dependent on the cabin pressure which would be falling at a logarithmic rate. This would also set an upper limit on the amount of gas lost since it would not be much higher than the initial amount in the cabin at the start of the leak. Figure 30 shows the mass of atmospheric gases (based on air) that would be present in a pressure cabin versus the volume of the cabin for various cabin pressures. In this method, the crew would have to don pressure suits, or resort to other secondary pressure protection prior to repairing the leak unless it was absolutely certain that the leak could be repaired before the pressure, either total or oxygen partial, fell below physiological limits. Figure 31 shows the rate of pressure decay for different size orifices for a free cabin volume of 1000 ft^3 and cabin pressures of 10 and 7 psia. As seen, for this size cabin, punctures in the order of 0.5 inches in diameter and larger require the crew to utilize secondary pressure protection immediately unless the leak can be stopped or at least reduced in a very short time. The net savings in atmospheric gases by allowing the cabin to decompress can be determined. For a 1000 ft^3 cabin, at 7 psia initially, and punctured by a 0.5 inch diameter hole, the gas weight loss would be 95.5 pounds in one hour if the pressure were maintained, but only 34 pounds in one hour if allowed to decompress, a net savings of 61.5 pounds. Also, the maximum loss, if decompressed irrespective of time would be limited to 36 pounds. This net savings decreases with a decrease in time and/or orifice diameter and vice versa as shown in Figure 32. (Note again that for Figures 30 through 32, a standard air composition was assumed for the cabin atmosphere. However, this introduces only a small error in the curves for the lower cabin pressures.)

It becomes evident that, to avoid an excessive loss of gases resulting from the larger punctures, the cabin must be allowed to decompress. The time allowed for the repair of the leak can then be relatively long, as the crew would be in pressure suits. However, there also may be leaks of such magnitude that, while not large enough to warrant a cabin decompression, would require immediate repair. In addition, there might be leaks of a minimal nature, important from a long term standpoint, but not requiring immediate repair. Thus, as the size of leak increases, there is first the minute leaks that can be repaired at the crew's convenience, next the larger leaks that require immediate repair and last the largest leaks, causing a cabin decompression, permitting a relatively long time to repair.

3.2.5 Warning Device

Two types of warning devices are required, one for the relatively large punctures which create a loss of cabin pressure, i.e., decompression, and another for the smaller leaks for which the cabin pressure is maintained. For the former, the alarm must be such as to initiate immediate response by the crew to don or utilize the secondary pressure protection system, be it pressure suits, encapsulating enclosures, or other means. Since some of the crew may

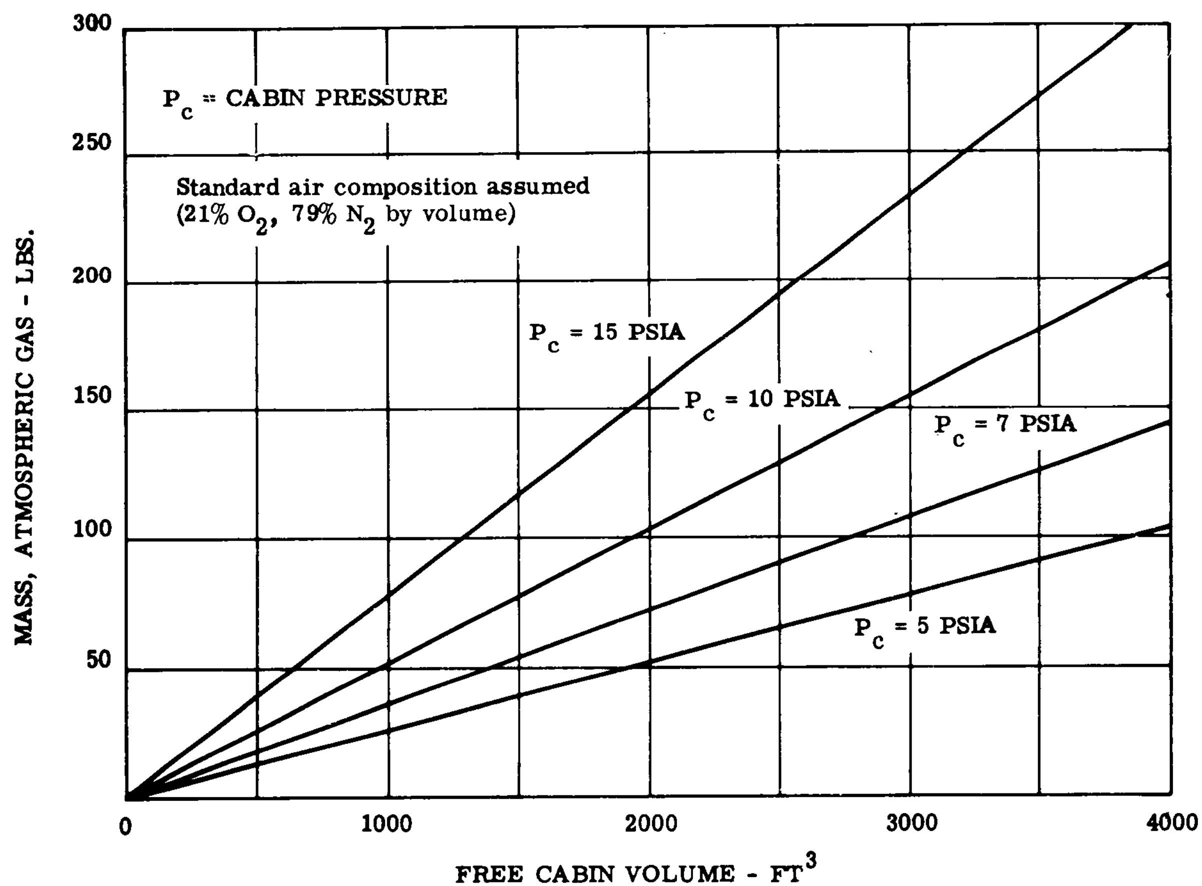


Figure 30. Mass Vs. Volume for Cabin Atmosphere

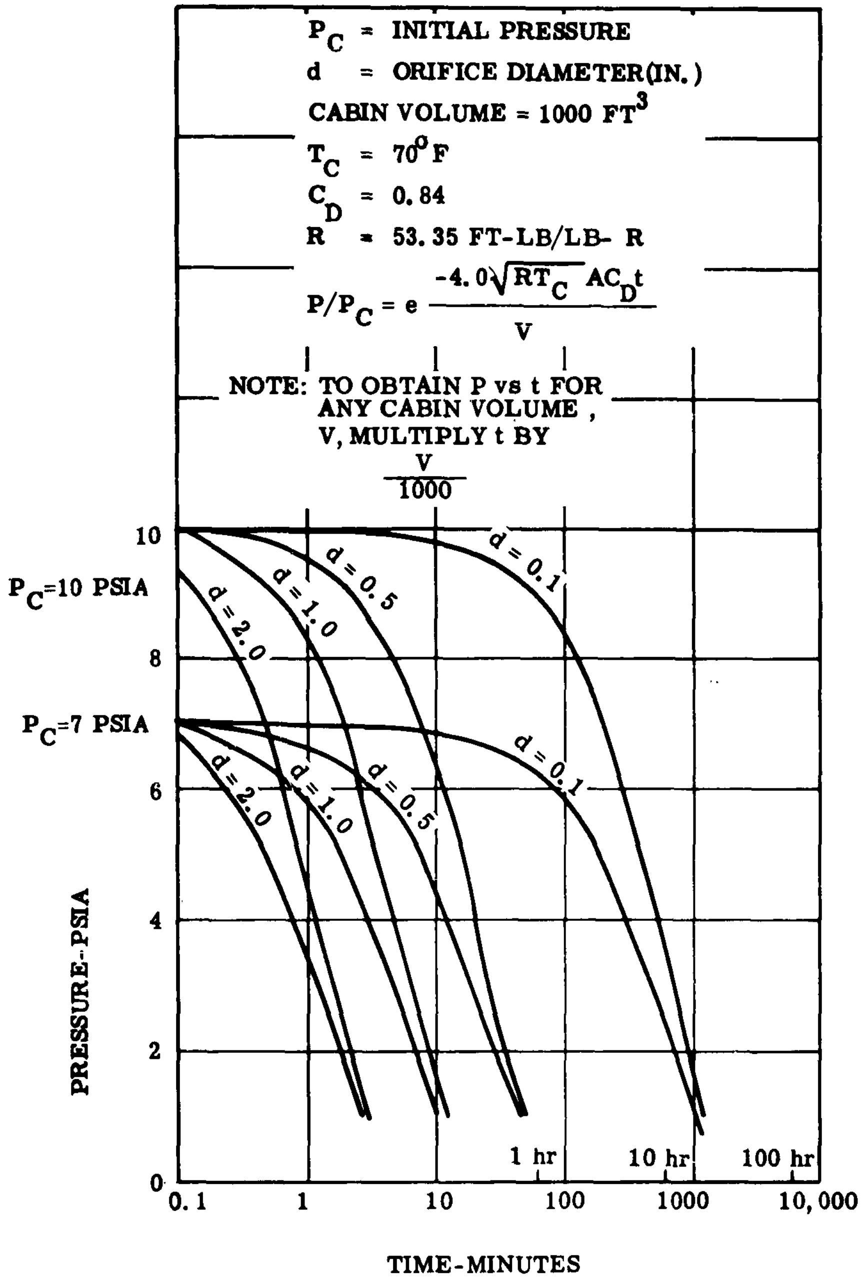


Figure 31. Pressure Decay - Standard Air Composition

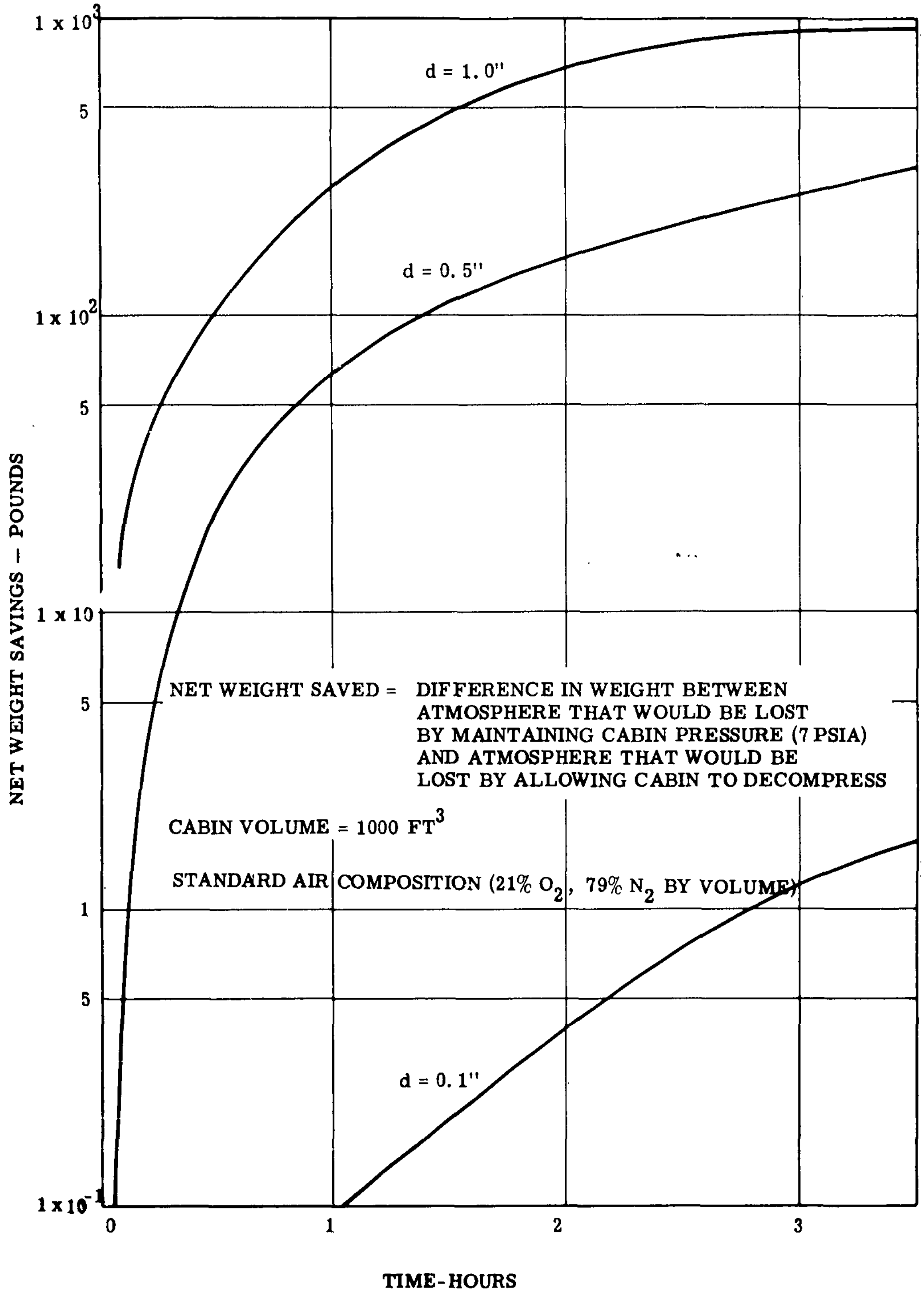


Figure 32. Net Weight Saved Vs. Time for Punctures of Various Diameters

be sleeping, the warning should be auditory and must be loud, raucous and irritating in order to gain immediate perception. A klaxon horn, or horns, with repeated honking should be ideal in this respect. This auditory system should be supplemented by indicator lights, although intensity of the light must not be sufficient to interfere with the astronaut's vision. Flashing lights would be particularly effective if the spacecraft were of compartmented construction, i. e., constructed with separate compartments which could be sealed off from the rest of the vehicle. The horns could be used to sound the general warning, and the indicator lights would be used to show at a glance which compartment was damaged and which were safe for occupancy. The crew could then retire to the safe area, seal off the damaged compartment, and have a relatively long time to don pressure protection devices prior to returning to repair the damage.

For the second type of leakage, less drastic measures are required. It can be assumed that a crew member will be assigned the task of monitoring the instruments recording the various aspects of the functioning spacecraft, such as life support equipment, propulsion system, communications, etc. at regular intervals. It would be relatively simple to add to this monitoring panel, an indicator that would signal the presence of a leak. It would be desirable also if this indicator could show the magnitude of the leak and its approximate location. Indication of magnitude is particularly important as the resulting action depends on this quantity. That is, a relatively large leak may require prompt repair whereas a small leak may be repaired at the crew's convenience. If there is a considerable time period between each visual monitoring of the flight instruments, which may result in the larger leaks remaining unnoticed for an undue length of time, an additional auditory warning will be required. A small buzzer or bell should suffice for this purpose.

The entire warning system must be capable of being tested and checked at regular intervals during the mission to ensure that it is functioning properly. Once the warning has been detected by the crew, the warning system, particularly the auditory devices, should be capable of being turned off to avoid an incessant buzzing or clanging. The visual indicators on the monitor panel should not be turned off in the case of a small leak since the crew members may forget its presence. It would be desirable to be able to selectively deactivate the warning system for that portion of the vehicle in which the leak is occuring, for it is conceivable though not probable, that another larger leak may occur while the detected leak is being repaired. If the warning system were deactivated for the entire vehicle, this leak would remain unnoticed until the first leak was repaired and the system reset.

3.2.6 Leak Location

The method utilized for the location of leaks must satisfy many requirements. First, the method must be fast, particularly for the larger leaks, to be consistent with the time for repair requirement. Second, the leak must be pinpointed sufficiently to apply the repair techniques. For the larger punctures, on the order of

1/16 inch diameter or larger, the pinpointing of the leak will not be too difficult as it would be visible to the naked eye. What is needed is an indication of the general location of these leaks, so that the crew will have an idea of where to look. It is quite probable that the puncture may be hidden behind equipment, in which case the general location of the leak is required to enable the crew to move the proper equipment away from the cabin wall.

For the smaller leaks, cracks, seal failures, etc. that cannot be located visually, at least not in a practical manner, a more elaborate method of location is required. Two alternatives to this problem are suggested. The leak can be precisely located, and the repair technique applied, or the general location of the leak can be found, and the repair, sealant or other material can be applied to the entire area in which the leak is occurring. The choice of these two methods depends on the study of leak location methods and repair techniques.

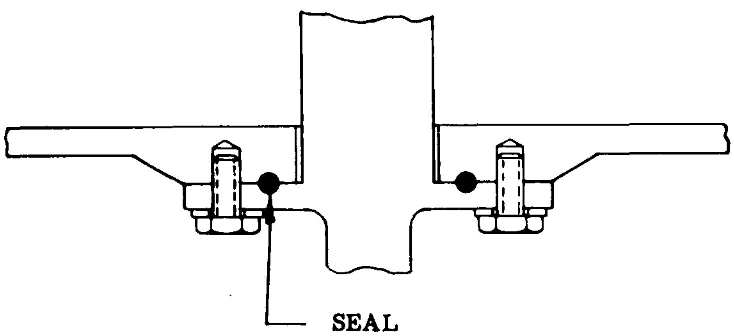
3.2.7 Leak Repair

The method utilized for the repair of leaks must be adaptable from the repair of small holes and cracks, to the repair of seals and large punctures. It may, in fact, be necessary to prescribe different repair techniques for different size leaks. For example, the extremely large and destructive punctures, where the structural integrity as well as the leak tightness of the cabin is impaired, would probably dictate repair of the structure by the welding, riveting, bolting, etc. of structural members in the damaged area. Leak tightness could be repaired using the same methods by welding or otherwise fastening a metal "patch" over the ruptured area. For very small leaks, on the other hand, pinpointing their exact location may be a problem, and thus a repair technique for sealing large areas of the cabin skin may be required.

Seals represent a special repair problem of their own. Figure 33 shows a typical cross-section of a seal. As can be seen, the elastomeric seal itself would not be visible. In practice the two seal surfaces are bolted, or otherwise firmly held together to assure good metal to metal contact. If the seal should fail, air could pass anywhere along this metal to metal surface, then around the seal at the point of failure and out to space. For repair, direct accessibility to the seal itself would require unfastening the seal surfaces, resulting in decompression of the cabin or, at least, a large loss of cabin air. Alternate methods would require either sealing the junction of the seal flanges, or adding a vaporific sealant to the escaping air that would solidify and seal at the point of failure.

Any method of leak repair should be permanent; that is, the repair, once made, should last for the duration of the mission. Some compromises to this may have to be made for the very long duration missions contemplated for the future, but complete permanency of repair should be the goal. The repair must, then, be able to withstand the environment of space as well as the stresses, vibration, shock, etc. of the space vehicle itself. Since the repair will be made on the skin of the manned space vehicle, the temperature seen by the repair material should be reasonable.

VACUUM



CABIN

Figure 33. Typical Seal

The repair material should be easy to apply since this is associated with the speed of repair, which must be as fast as possible as mentioned previously. In this respect if a liquid sealant is contemplated for use, it should be relatively quick setting in order to prevent excessive loss of air. Many types of sealant materials contain components which volatilize upon solidification. Care must be exercised to ensure that these volatile components which outgas are not toxic.

3.2.8 Complexity and Reliability of System

The leak detection, location and repair system must, like any other spacecraft system, exhibit a high reliability, or conversely, a low probability of failure. Axiomatically, the system should be as simple as possible, for as the complexity of a system increases, its inherent reliability decreases. It should be recognized that the safety of the crew may quite possibly depend on the timely repair of cabin leaks, for, if they are a considerable distance from earth, it is problematical whether suitable secondary pressure protection could be used for the crew on the long trip home. Even if the crew could survive a condition of excessive leakage, it would be very costly to abort the mission. Thus a dependable, reliable repair capability for leaks is required.

It may not be required to provide the crew with the capability to repair the larger ruptures of the cabin. Secondary effects of rapid decompression, flying debris, explosion or equipment damage could be fatal to the crew in which case, obviously, no repair is required. The probability of these occurrences should be very low, of course. That is to say, there will always be hazards in space flight, but the dangers will be minimized as far as is practical.

The reliability of the system should be maintained throughout the environments to which it will be subjected. It has to withstand shock, acceleration vibration, temperature cycling, vacuum and possibly radiation without failing. Redundancy can be used where practical to increase the system reliability. Some redundancy will probably be inherent. For example, the atmosphere make-up supplies should have a quantity gaging system which should, over a relatively long period, indicate the cabin leak rate. From this the crew could determine if the cabin had sustained a leak. Also, the leak detection and location system should be capable of being checked, i. e., tested, at intervals to assure that it is functioning adequately. Then if a malfunction exists, the ability to repair and return the system itself to operating condition would increase its reliability.

IV. DETECTION, LOCATION AND REPAIR TECHNIQUES

4.1 INTRODUCTION

There are many different methods that could be used for detecting, locating and repairing leaks in a manned space vehicle cabin. In the following section of the report each of these methods is examined. Included in techniques for repair of the leaks are various forms of patches, plugs, sealant putty and liquid adhesive sealants. For detecting leaks, methods sensitive to the loss of atmosphere, such as measuring parameters affecting the diluent utilization rate, or acoustic techniques, or pressure sensing devices located external to the cabin, as well as methods sensing continuity of the cabin wall, such as ultrasonic inspection, or continuity sensors, are investigated. Some of the above detection methods will locate the leak within a general area. Methods discussed for further pinpointing the leak include industrial inspection techniques, various coatings that can be applied to the wall, and acoustic methods.

4.2 REPAIR TECHNIQUES

The types of repairs required can generally be divided into three categories, according to the type of leak. These will be (1) repairs for large punctures of the cabin wall, (2) repairs for small punctures and cracks, and (3) repair of seal leakage. The methods for repairing these different types of leaks need not be the same, but it would be desirable, in order to reduce complexity, to utilize the same materials or methods to repair all leaks. Methods of leak repair will be discussed now.

4.2.1 Large Punctures

Large punctures of the pressure cabin would be caused by meteoroids and/or various structural catastrophies, such as collision during rendezvous or internal explosion. Depending on various parameters, size of hole, cabin volume, etc., the cabin may or may not become decompressed due to the large leakage resulting. The method of repair, then, should be capable of being applied while subjected to vacuum or low ambient pressures, as well as when the cabin is fully pressurized.

The puncture is likely to be irregular in shape and exhibit roughness or surface irregularities along the inside lip of the hole. Refer again to Figures 11 through 22 as they illustrate puncture formations created by hypervelocity impacts in actual tests conducted at GE-MSD. These figures show that the inner surface of the pressure cabin wall immediately surrounding a meteoroid puncture will probably be rough (i.e., not flush with the wall). Then too, in the case of large punctures created by causes other than meteoroids, the pressure skin may be punched, ripped, torn, jagged, bent, etc., and will most likely not form a clean hole.

Two different techniques are available for the repair of these large punctures, and can be loosely described as plugs and patches. The plug would fill the hole, similar to a cork in a bottle, while the patch would cover the hole, and adhere to the wall immediately surrounding the puncture.

For a plug to be used successfully, however, the puncture must be round, or nearly so, in order to obtain a good seal between the plug and the pressure wall. This means that, for irregularly shaped punctures, the holes must be drilled out (i.e., enlarged until they are round). Some irregularities may be allowed to exist if the plug is covered with sealant after insertion into the puncture. Such a repair is illustrated by Figure 34. The type of sealant would have to be a fast curing putty adhesive which could be brushed, troweled, or applied with the fingers. (More will be said on sealants later.) Plugs would most probably work best for meteoroid punctures, where in some cases the hole would be almost round to begin with, while plugs may not be applicable for other types of punctures where extensive rework of the leak area is required.

A self brazing plug (Figure 35) could also be used to seal large leaks. The plug would have a lip which, when inserted into the hole, would contact the cabin wall. On this lip would be the brazing material. On top of the plug would be a chemical fuel, which could be ignited with a small battery and covering this would be a layer of insulation. The plug would be inserted into the hole, the fuel ignited, and the plug brazed automatically to the wall. Special devices may be required to hold the plug snugly against the wall when brazing. Rework of the leak is required prior to installation of this device. Possibly only one or two sizes of these plugs are required since the puncture can be drilled or reamed out to accommodate a given size plug. Because of the rework required, it is doubtful if this repair can be made when the cabin is pressurized, but rather it would be more useful for large punctures wherein the cabin is decompressed.

Patches are the remaining alternative to the repair of large punctures. They could take many forms. If the puncture is small enough so that the cabin remains pressurized, the repair will have to be quick and adaptable to the irregularities of size and shape that can occur. If the leak is large, and the cabin depressurized, time could be taken to clean up the damaged area prior to repair.

For the former, a mastic or putty-like adhesive sealant can be smeared over the puncture. The putty should be thick enough to resist extrusion through the hole, should have excellent adhesion to the wall, and should cure to form a tough durable seal. Molding the putty over the sharp, jagged edges would present no problem. Several types of "hollowed-out" or depressed center patches could also be devised. The patch would be permanently recessed in the center so that the patch would contact the cabin wall around the puncture, then the bent edges of the wall would protrude into this recessed area. The patch could be made out of metal or an elastomeric material and would have to be bonded to the wall.

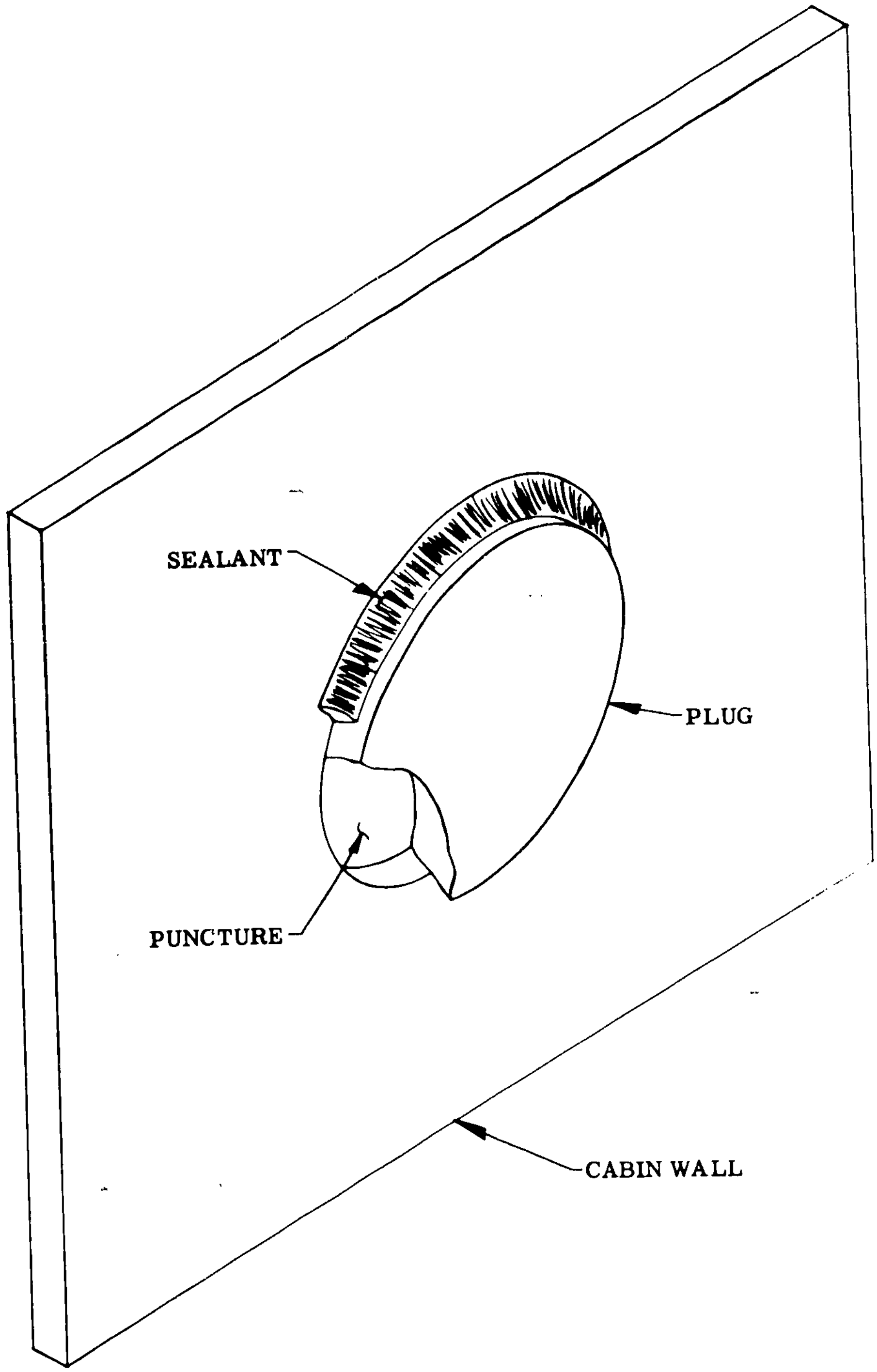


Figure 34. Plug Patch For Round Hole.

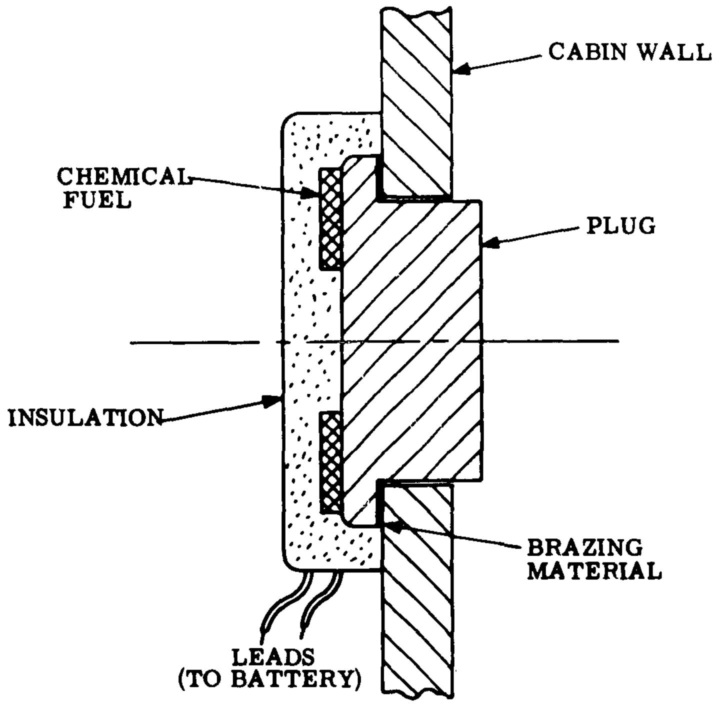


Figure 35. Self Brazing Plug

An elastomeric patch of sufficient flexibility that could "snug down" over the puncture might be used also. This patch would have to combine flexibility with toughness, however, to prevent tearing of the patch by the sharp edges. For permanency and reliability of sealing the patch should probably be bonded to the wall with an adhesive sealant.

If time can be taken to clean up the punctured area (i.e., rework it so that the puncture is flush with the wall), a metal or elastomeric patch can be bonded over the hole. Two requirements must be met. They are, one, that the patch be flexible enough to conform to the wall contour, and two, that they be strong enough to resist the cabin pressure. A strong metal patch can be made by fastening it to the wall with blind mechanical fasteners, such as rivnuts. The patch-wall surface would be coated with sealant and the fasteners would draw the patch to fit the contour of the wall. The fasteners themselves would be sealed with O-rings as shown in Figure 36. This installation would require more time than simple bonding but would have some structural use as well as being leaktight.

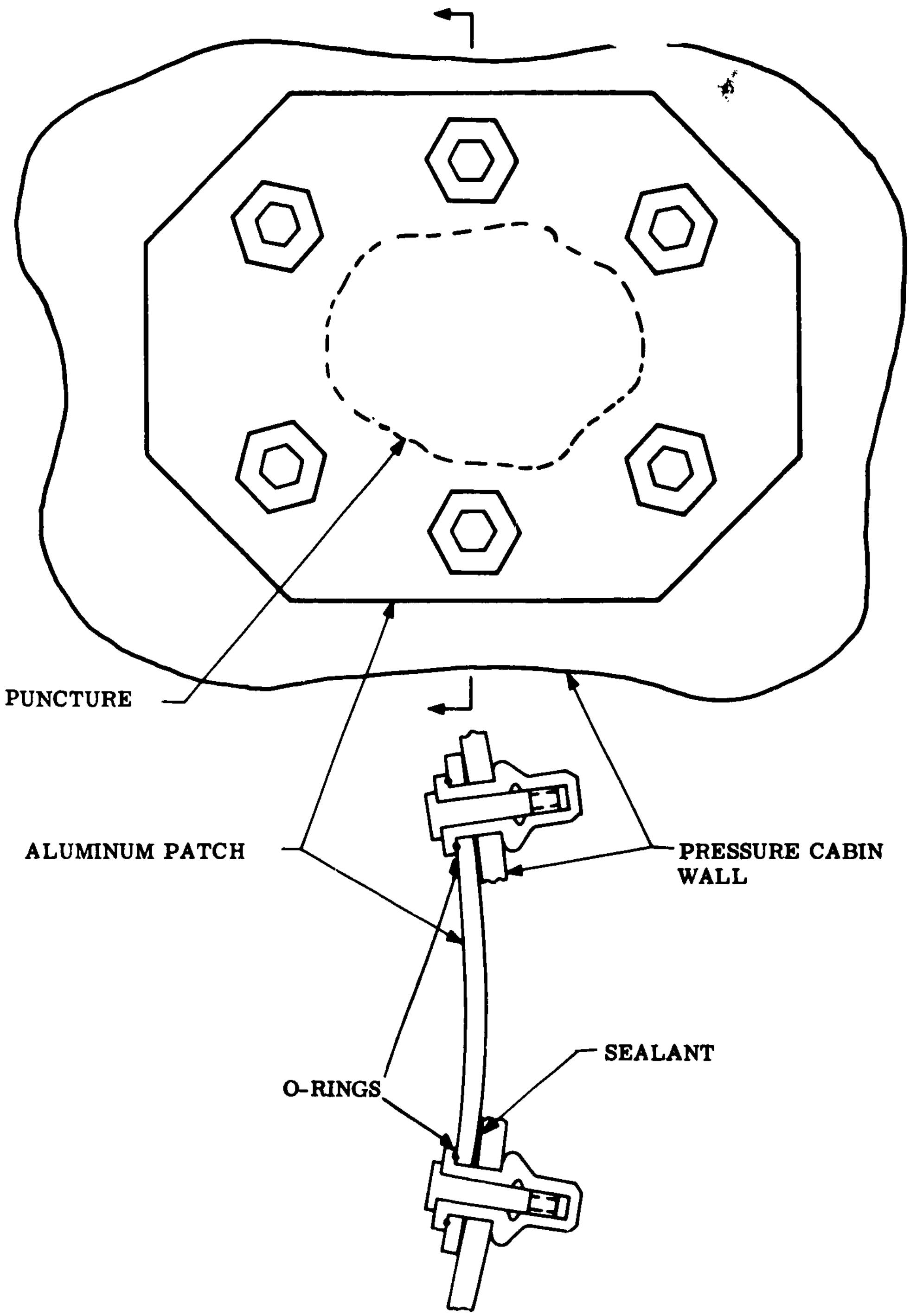


Figure 36. Mechanically Secured Metal Patch.

4.2.2 Small Punctures

The method of repair of small punctures and holes depends, to an extent, on the preciseness with which the hole may be located. Certainly, the general area in which the leak is occurring must be known to keep the repair short of sealing the entire vehicle wall. The repair of small punctures, then, reduces to either a method for sealing relatively large areas in which the puncture occurs, or of sealing a small hole whose exact location is known.

Taking the former case first, it will be assumed that the general location of the leak will be known. Further, if the leak is of substantial size, on the order of 1/16-inch diameter or larger, it can be further located visually. The sense of touch can also be readily used to locate the leak, as a degree of roughness should be expected around the puncture. Thus the leak requiring sealing of a large area will be of the pin-hole size or smaller.

Various types of sealants should work well to seal these small holes. The sealant would be applied to the area in which the leak is located. It could be sprayed, brushed or troweled on the surface to form a uniform coat. Zero-g considerations would have to be included in the method of application, of course. For example, special devices would be required if the sealant were brushed on to keep the sealant from splashing from its container. An applicator could probably be designed in which the brush would be an integral part of the sealant reservoir. The liquid sealant would travel from the reservoir to the brush by wicking action, or, if necessary, by a pressure force exerted by a plunger or other means. The brush would be capped when not in use. Troweling compounds, which would have the consistency of paste or putty, rather than liquid, could be available in tubes, from which the compound could be squeezed.

A simple spray can of sealant might be the easiest and quickest to apply. The spray could deposit the sealant uniformly on the wall, perhaps forming a tough plastic film. Care would have to be taken, of course, to insure that any spray droplets that might be released in the cabin atmosphere would not harm any of the operating equipment. A tent or hood could be used while spraying to prevent the random distribution of the droplets to the cabin air.

Another method which might be used to seal off large areas would be to mask off the area using a plastic film, such as mylar, or other suitable material. The sheet would be taped, or otherwise sealed around its periphery, and cover the entire area. This method would not work too well if services, such as cables, tubing, etc. extend through the area to be sealed. There also might be a problem in covering different items that protrude from the wall such as structural members, connectors, etc.

If the exact location of the puncture is known, the method of sealing becomes simpler. A dab of sealant, in this case a paste or putty type could be applied to the hole, or a small patch of rubberized material or tape pressed over the puncture, or both. The choice depends on suitable selection of materials.

4.2.3 Cracks

The leakage from cracks can be stopped in much the same manner as small leaks; that is, a liquid sealant could be sprayed or brushed on, or a paste sealant troweled on over the crack. An elastomeric patch or tape could also be used. This latter method may not be as practical, however, since the crack may terminate at or pass by, electrical connectors, stringers, rivets, weld beads, etc., which would make a seal difficult using a patch. The paste sealant, on the other hand, could conform to any irregularity.

There is a possibility, too, that the crack may weaken the structure to the point where structural repair is required. In this case, one or more plates, serving as doublers could be fastened over the crack. Prior to fastening, the adjoining surfaces of doubler and wall should be coated with sealant to prevent air leakage as well. Another method of repair could be to repair the wall by running a weld right along the crack. This could be difficult to accomplish if the cabin remains pressurized, however, as the weld would "blow out." Then too, a coat of sealant would probably be required over the weld bead to insure an adequate seal.

4.2.4 Seals

In order to repair a seal that is leaking excessively, one of two things may be done. First, the seal may be replaced, or second the cabin pressure wall must be resealed directly to the component which is penetrating the wall. The former may be practical for some seals in the space cabin and impractical for others. In general, it would be impractical to use replacement of the seal as the method of repair when decompression of the cabin would result, although, in some cases there may be no alternative. Seal replacement would be most practical for the seals in airlocks, and other components, where the cabin would not have to be decompressed in order to replace the seal.

The second method requires resealing the wall with the component, be it connector, pipe, tube, etc., that passes through the wall. This could be accomplished with sealing compound. Ideally, the sealant could be applied around the periphery of the junction of the seal surface flanges, but it could also be applied between any convenient wall-component joint. Also, the sealant has to be applied 360 degrees around this joint, in order to seal it adequately. If the component is an item which must be capable of being removed quickly, such as an escape hatch, the sealant will have to remain pliable enough so as not to interfere with this operation.

The above technique should be applicable to any fixed component, but would not apply to seals for rotating or extendable shafts, such as may be used for periscopes, antennas, etc., where the component moves in relation to the cabin wall. Repair of these seals would be difficult unless the seal itself could be reached with sealant, either introduced in the leaking air stream, or applied directly. Alternatives would be to reseal the component with sealant each time that it is moved, or allow the cabin to decompress and replace the seal. The design of these components should take seal repair into consideration.

4.3 LEAK DETECTION METHODS

4.3.1 Leak Rate by Monitoring Atmospheric Composition

If the space vehicle maintains a two-gas atmosphere (i. e., oxygen plus a diluent), it is possible to determine the leakage rate by a pressure decay method utilizing the diluent gas. In this method, the diluent supply would be turned off so that no make-up could be admitted to the cabin, and the rate of the partial pressure decay of the diluent observed. From this, the cabin leak rate can be determined as follows:

$m_o = \rho_o V$ lbs where m_o = mass of diluent, initial - lbs

ρ_o = density of diluent, lbs/ft^3

V = cabin volume - ft^3

and $\rho_o = \dfrac{P_o}{RT}$ where P_o = partial pressure diluent, initial- lbs/ft^2

R = gas constant, diluent, ft-lbf/lbm-^oR

T = temp - ^oR

for final conditions

$m = \rho V$ and $\rho = \dfrac{P}{RT}$

and

$$m_o - m = \left(\frac{P_o}{RT}\ V\right) - \frac{PV}{RT} = \frac{V}{RT}\ (P_o - P)$$

The average diluent leak rate, w (lbs/min), is

$$w = \frac{m_o - m}{t} = \frac{V}{RTt}\ (P_o - P) \quad \text{where } t = \text{time - min.}$$

to find the total leak rate, w_T, lbs/min

$$w_T = \frac{w}{1/2} \frac{P_r}{(P_o + P)} \quad \frac{M_{mix}}{M}$$

where P_r = nom. cabin pressure - lbs/ft^2

M_{mix} = molecular wt. of cabin atmosphere

M = molecular wt. of diluent

The above equation holds true if the diluent pressure decay is linear with time. Actually, the pressure decay will be a logarithmic function of time, but for small P_o - P, it can be assumed to be linear.

Converting w_T to cc/min

$$w_T = \frac{2w\,P_r}{(P_o + P)} \left(\frac{M_{mix}}{M}\right) \frac{28,316}{\rho r}$$

where ρr = nominal cabin density-lbs/ft^3

and $\rho r = \frac{P_r}{R_{mix} T}$

so that $w_T = \left(\frac{2\ V}{RTt}\ \frac{(P_o - P)\ P_r}{(P_o + P)}\right)\left(\frac{M_{mix}}{M}\right)\left(\frac{28,316\ R_{mix}\ T}{P_r}\right)$

now $R_{mix}\ M_{mix}$ = universal gas constant = RM, and simplifying

$$w_T = 56,632\left(\frac{V}{t}\right) \frac{(P_o - P)}{(P_o + P)}\ \text{cc/min}$$

To obtain an idea of the manner in which this technique could be applied, the following values will be chosen as typifying an actual vehicle.

Cabin Atmosphere	P_r	= 360 mm Hg
	pO_2	= 180 mm Hg
	pCO_2	= 1 mm Hg
	pH_2O	= 9 mm Hg
	$P_o = pN_2$	= 170 mm Hg

Cabin Volume = 1000 ft^3

Note: pCO_2 and pH_2O will normally vary, but during the time in which the leak rate measurement is taken, they will be considered constant. Any actual variation would result in an error in the result.

Now, at the start of the measurement, the make-up N_2 supply is closed, and P_o = 170 mm Hg. The elapsed time for the pN_2 to drop 5 mm Hg is then measured, so that P = 165 mm Hg. The leak rate versus time can then be obtained by the plot of Figure 37. Since a 1000 ft^3 cabin will house, perhaps, three men, and current leak rates are estimated at about 500 cc/min/man, the range of interest is between leak rates of 500 to 1500 cc/sec, or time of 10 to 30 hours. Thus the time required to determine the leak rate is very long. It can be shortened by reducing P_o - P to less than 5 mm Hg, but this would increase the error in the result, due to limitations of the pN_2 sensing equipment.

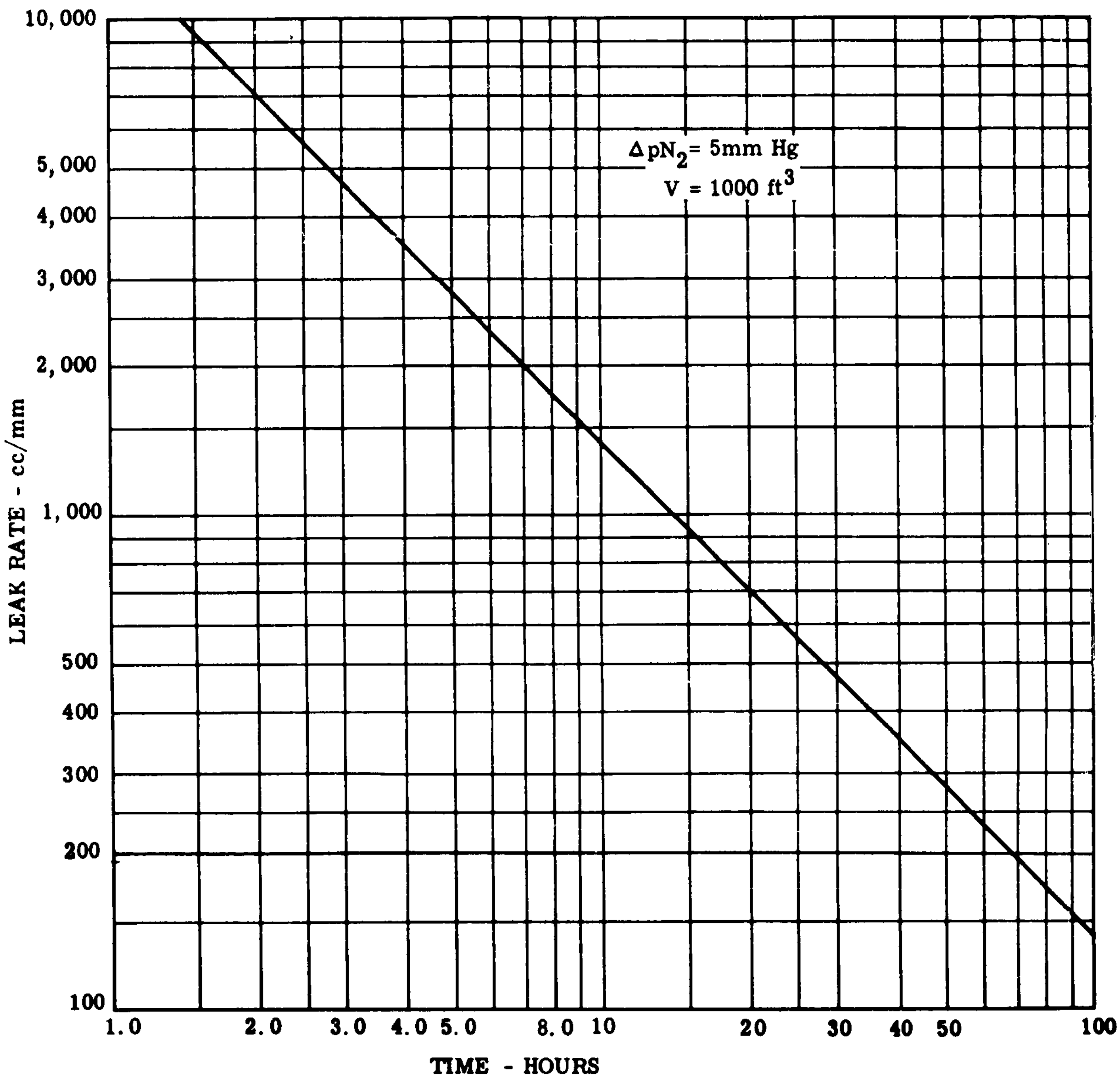


Figure 37. Leak Rate Vs Time.

4.3.2 Leak Rate By Measuring Diluent Supply Rate

Since the only loss of the diluent gas in the cabin will occur through leakage, it is possible to determine the leak rate if the rate of diluent usage can be measured. If the diluent is admitted continuously to the cabin, by means of a controllable orifice, or controllable pressure behind an orifice, it would be relatively simple to determine the leak rate. The atmosphere control system, in this case, maintains the continuous flow of diluent so that the entering rate equals the diluent leakage rate, which, when multiplied by a suitable factor to include oxygen leakage also, yields the total cabin leak rate. This system is represented by Figure 30. The pressure regulator, pressure reducer, or controlled orifice, whatever it may be, receives an error signal from the atmosphere sensing and control unit which is translated by the regulator to higher or lower pressure in the line behind the fixed orifice depending, respectively, upon whether a higher or lower diluent supply rate is required. The pressure transducer senses the pressure behind the fixed orifice, and since this pressure is directly proportional to the diluent flow rate and hence, also, to the total cabin leak rate, the signal from the transducer can be calibrated directly to give the cabin leak rate.

The advantages of this system lie in the fact that the overall cabin leak rate can be conveyed to the crew instantaneously during a steady state condition. Even if no leaks developed, it should be a great comfort for the crew to know that the cabin leakage is within the limits of their atmosphere supply capability. If a leak occurs, some time lag will exist in this system due to the time constants required to prevent overshoot and cycling of the diluent partial pressure. This means that the time required to detect a leak will be something less than immediate. However, the relative magnitude of the leak can be determined by the step change in the leak rate. Problems will probably exist, too, in the design of the variable pressure mechanism due to the small flow rates required.

Because of the small flow rates, the diluent supply system will probably be designed to cycle. That is, the diluent will be admitted in discrete amounts at definite intervals. This system can still be instrumented to show diluent leak rate, however, as shown in Figure 39. In this system, the demand regulator maintains a constant pressure in the line behind the fixed orifice. The solenoid valve receives a signal from the atmosphere sensing and control unit (which could be based on either diluent partial pressure or cabin total pressure) to open when the partial pressure or total pressure reaches a set minimum or close when it reaches a set maximum. Thus, the diluent partial pressure will vary between set limits. Since the pressure behind the orifice is regulated (i. e., constant), the amount of diluent admitted is proportional to the total time that the solenoid is open. The pressure transducer would supply a correction factor should the regulated pressure shift slightly from the nominal value.

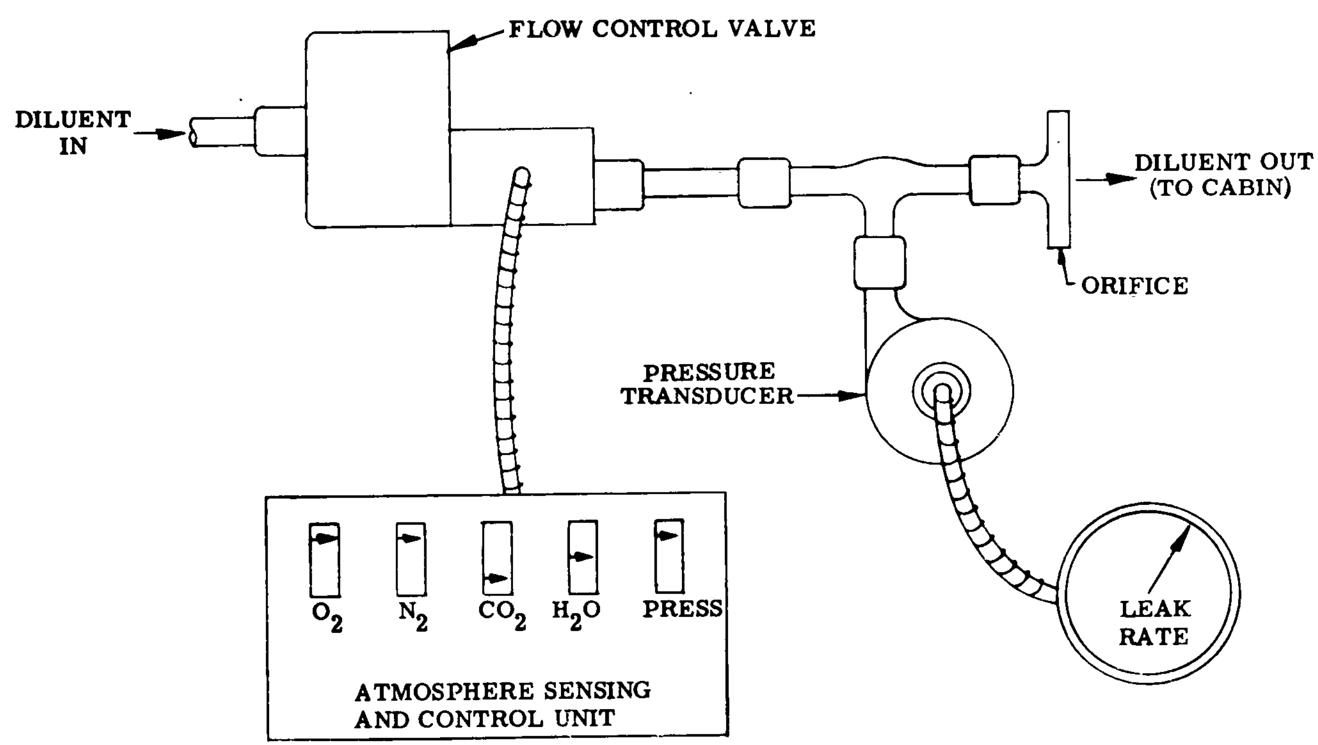


Figure 38. Continuous Flow Diluent Supply Leakage Detection.

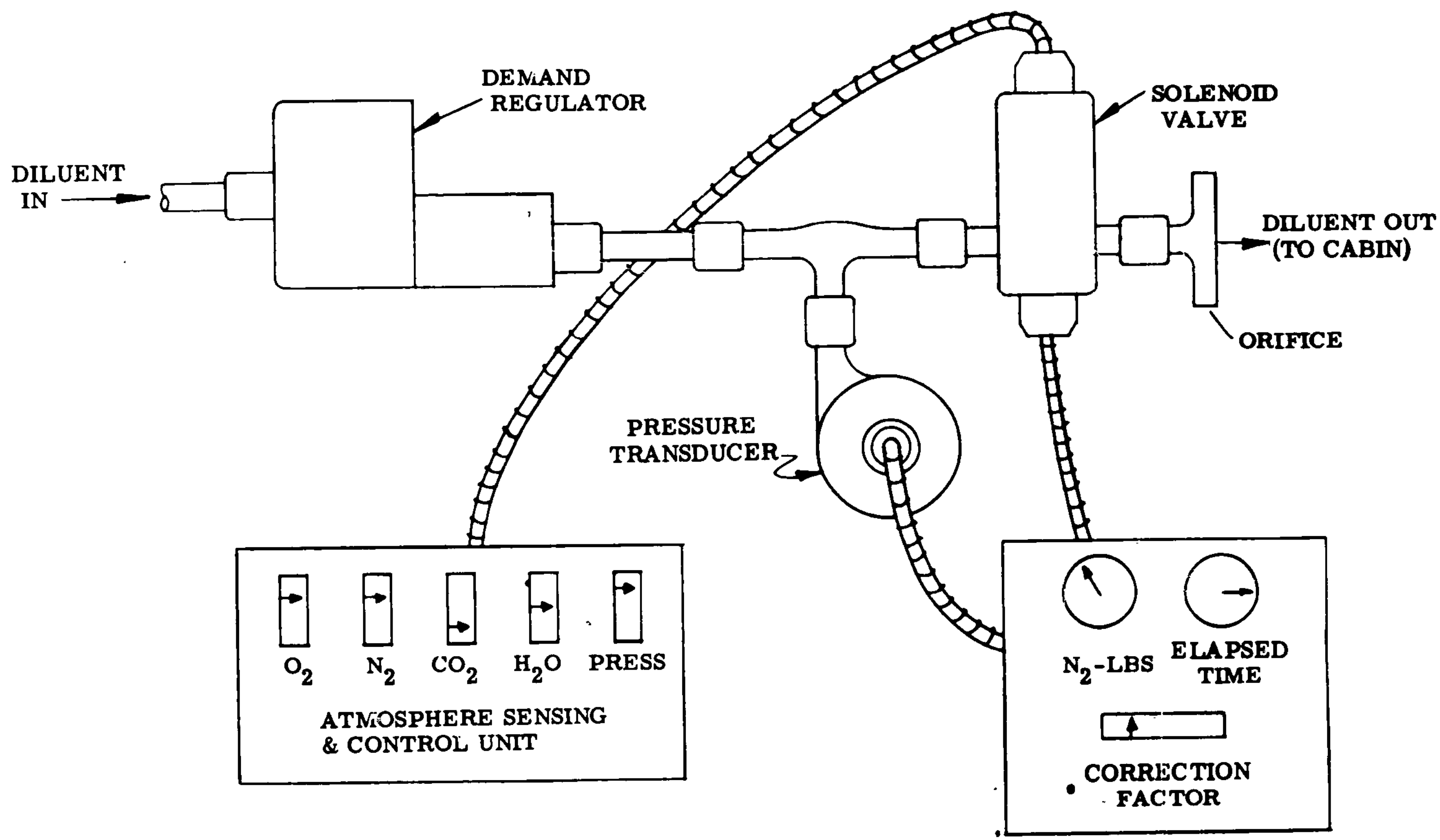


Figure 39. Cycling Diluent Supply System

In practice, to determine the leak rate, the timing would start just after the solenoid valve closes at the end of one cycle. The total elapsed timer would start, and the system would be "armed" to record the total time of solenoid operation. After several cycles, the test would end as the solenoid closed at the end of one cycle. Several cycles would be necessary in order to smooth out errors in the diluent sensing equipment. (If solenoid operation is based on total pressure, more cycles would be required, because of the variation in total pressure created by the separate O_2make up supply). The total amount of diluent admitted would then be divided by the total elapsed time to yield the leak rate. This could be done automatically by a mechanical computer, or by the crew if desired.

This method of determining the leak rate is of dubious value for use in leak detection, however, as it takes a long time to obtain a valid reading. For example, for a typical cabin of 1000 ft^3 volume, leaking 1000 cc/min at a cabin pressure of 360 mm Hg (170 of which is N_2, the diluent), if the ΔpN_2 were established at 1 mm Hg between solenoid on and off positions, it would be about 2 3/4 hours between cycles. As several cycles are needed, the time becomes more excessive.

It can be concluded that determining the cabin leak rate by monitoring the atmospheric composition in a pressure decay type of system, or by measuring the amount of diluent make up is not very satisfactory for the purpose of leak detection, unless the leak is of substantial size to cause a gross effect that would greatly decrease the length of time required in the determination. The one method of diluent supply, where the diluent is fed continuously in a steady supply to the cabin has some promise, but is the most difficult to achieve with practical hardware. There is also a great chance in all these methods for error to creep in due to drift or calibration in the atmosphere sensing equipment, or change in pressure regulation due to the small Δ P being measured and the side influence of the separate O_2 supply on cabin total pressure. Needless to say, these methods would not locate a leak either.

4.3.3 Ionization Gauge Leak Detector System

The ionization gauge leak detector essentially detects any minute increase in pressure on the outside of the pressure cabin hull caused by leakage from the inside through the wall. Figure 40 shows schematically the basic method of operation. Shown is a puncture that may be caused by a meteoroid, creating a small leak in the pressure cabin. The cabin air escaping from this leak expands rapidly, some passing through punctures, holes, gaps, etc., in the outer wall and some filling the space between the two walls. The electrodes of the ionization gauge are maintained at a suitable potential to ionize the air molecules between them, and thus current flows in the electrode circuit. This, in turn, actuates a relay which closes the alarm circuit signaling the presence of a leak. A suitable grid network of electrodes can be spaced around the periphery of the space cabin to give the needed additional information as to the approximate location of the leak.

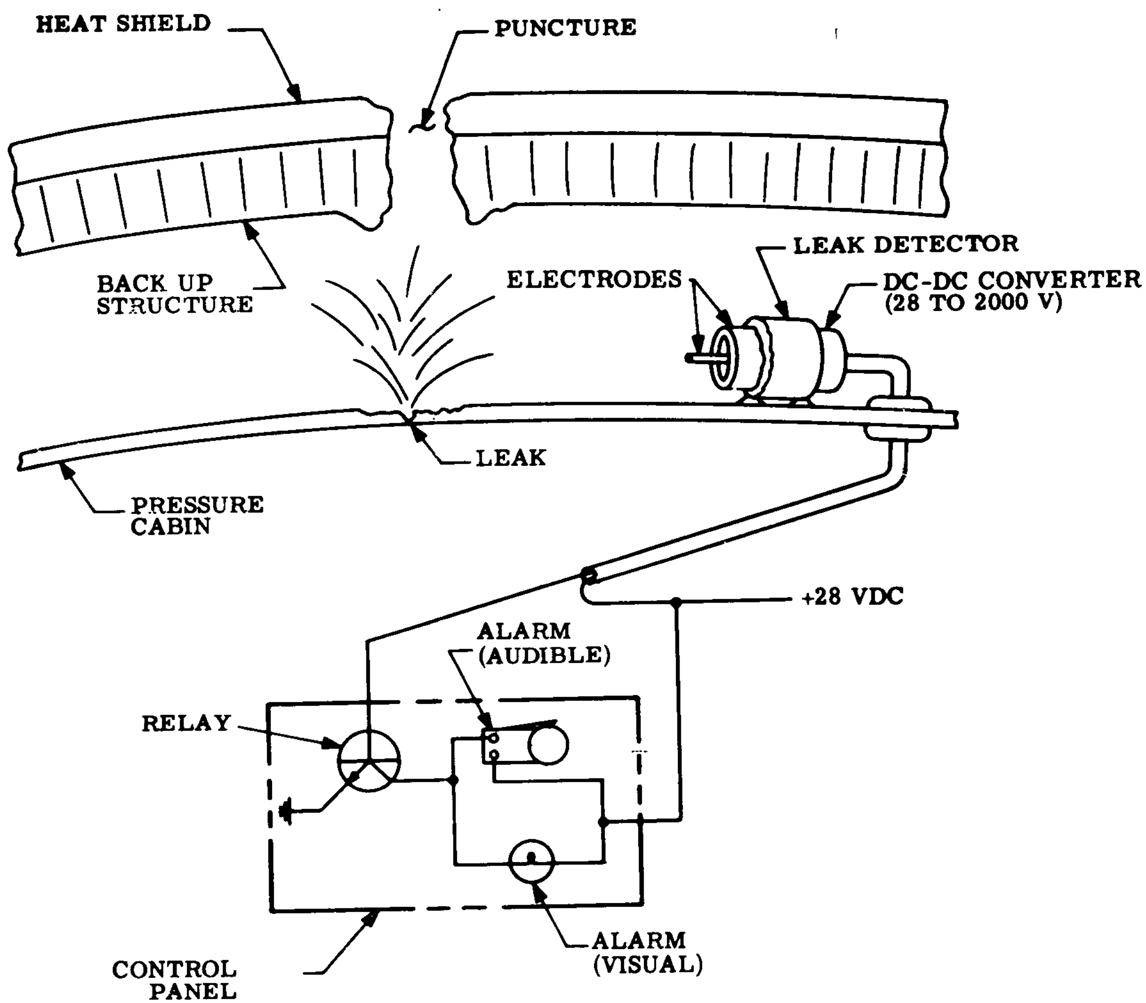


Figure 40. Basic Concept - Ionization Gauge Leak Detector

This type of leak detection system was studied in reference 16 and determined to be feasible. The electrode or gauge design was based on the Phillips Ionization Gauge. This detector utilizes high field emission from a chemically active cathode under a potential of 2000 volts to emit electrons that are deflected and cover a longer path from cathode to anode than would otherwise occur. This enhances the chance for collision with a gas molecule and subsequent ionization and thus raises the sensitivity of the gauge. A Phillips Ionization Gauge can easily detect pressures down to 1 x 10^{-5} mm Hg. A grid network of these gauges spaced around the cabin could detect leaks on the order of 0.001 to 0.01 lbs/hr. Higher sensitivity can be obtained if required either in the Phillips Gauge or in substituting a different type of high vacuum gauge, such as a hot filament ionization gauge.

4.3.4 Leak Detection By Discontinuity Sensors

There are several methods available for the detection of leaks that utilize the puncture itself to make or break electrical continuity, and thus trigger, electrically, a leak alarm. One such arrangement uses a thin mylar sheet about 1/3 mil thick, to separate the metallic wall from a metal sheet (see Figure 41). An electrical potential is applied between the wall and sheet (i.e., across the mylar). Since the mylar is a good insulation, no current will flow initially. When a puncture occurs, the force of the blow mashes, crimps, or fuses the wall and metal sheet together, connecting the circuit. The resulting current actuates the alarm. Separate isolated "detectors," consisting of the mylar and metal sheet can be used to cover the cabin wall area. This would then give the crew the general location of the leak as well, for it would be easy to display which panel was punctured.

The advantages of this system are that relatively low voltages and passive circuitry are used to increase the reliability, and that the signal (i.e., current) after the puncture is continuous, requiring no flip-flops or fast reacting relays. There are several disadvantages. One disadvantage is that all fastenings that attach, or pass through the wall would have to be insulated from the potential carrying metal, to prevent a short circuit. Quite obviously, the detector panel itself has to be fastened to the wall which would require insulated fastenings, if fastenings are used. Another problem is that of resetting the detector panel after a puncture, that is, repairing the short circuit so that the detector will be able to sense another puncture. This would be difficult, short of replacing the entire panel, and add to the time required for the repair of the puncture. An alternative is to have many detectors, each covering a small area so that the probability of being punctured twice in one detector in one mission would be extremely low.

The reliability of this system for detecting punctures is based on the consistency with which the two metal sheets form a short circuit (i.e., create electrical continuity), when a puncture occurs. This reliability is difficult to evaluate without actual testing information.

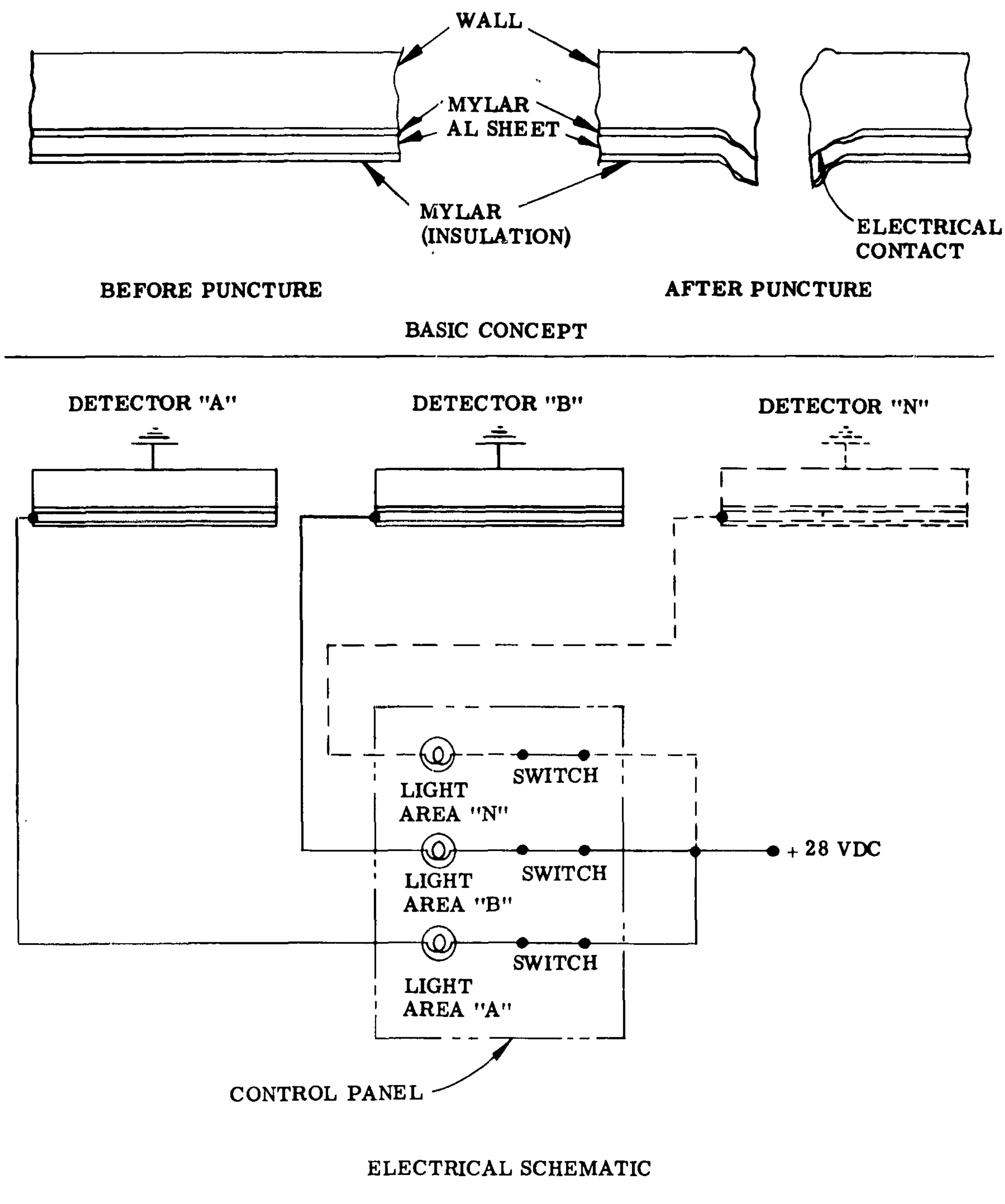


Figure 41. Continuity Sensor - Electrical Contact

The many effects of a meteoroid impact, spalling, heat, vaporization, etc., may or may not allow the required degree of consistency. Another method may be devised which does not depend on actual electrical contact being created. In this technique, shown in Figure 42, a mylar film, aluminized on one side, covers the cabin wall area. A high voltage is impressed on the aluminized surface so that the system is charged like a capacitor. When a puncture occurs, the capacitor is discharged by a spark discharge across the air gap, since mylar has a much higher dielectric strength than air. In the process of discharging, a transient current will be built up in the circuit, which triggers the bi-stable multivibrator corresponding to the detector. Because of the capacitor in the line, the current will cease when this capacitor charges up to the point where the voltage potential across the air gap in the mylar no longer is high enough to sustain the discharge. The function of this capacitor, then, is to stop any current (i.e., power drain), once the initial current pulse has been detected.

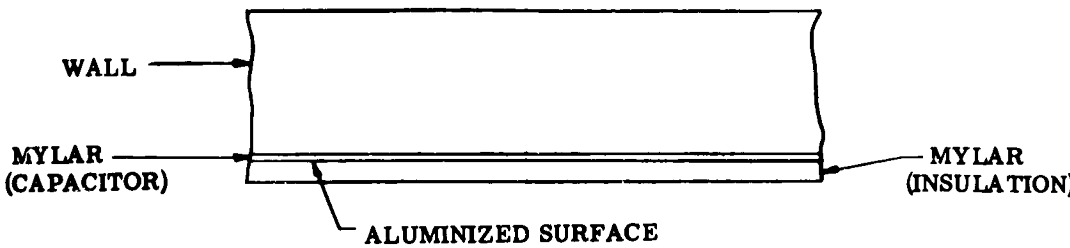
Since there will probably be a potential left between the wall and aluminized surface of the mylar (i.e., across the air gap) after a puncture, it may be necessary to short the wall and aluminized surface by means of a relay to prevent the possibility of shocks to the crew during repair action. The relay would be closed by a signal from the multivibrator and could be the same signal that actuates the panel warning light. After repair, the relay could be reset to conserve power. The relay would be useful, too, for checkout of the system during flight.

The aluminized mylar film can be sectionalized into, perhaps, one foot square segments, where each segment would be a separate detector. There are two advantages to this: one, the puncture can be located quickly with relative precision, and two, it eliminates the need for repairing the detector once broken because the probability of sustaining two punctures in such a small area in one mission is very low. It is possible that a high dielectric strength sealant material, pressed into the puncture could return the detector to its original condition (i.e., a capacitor).

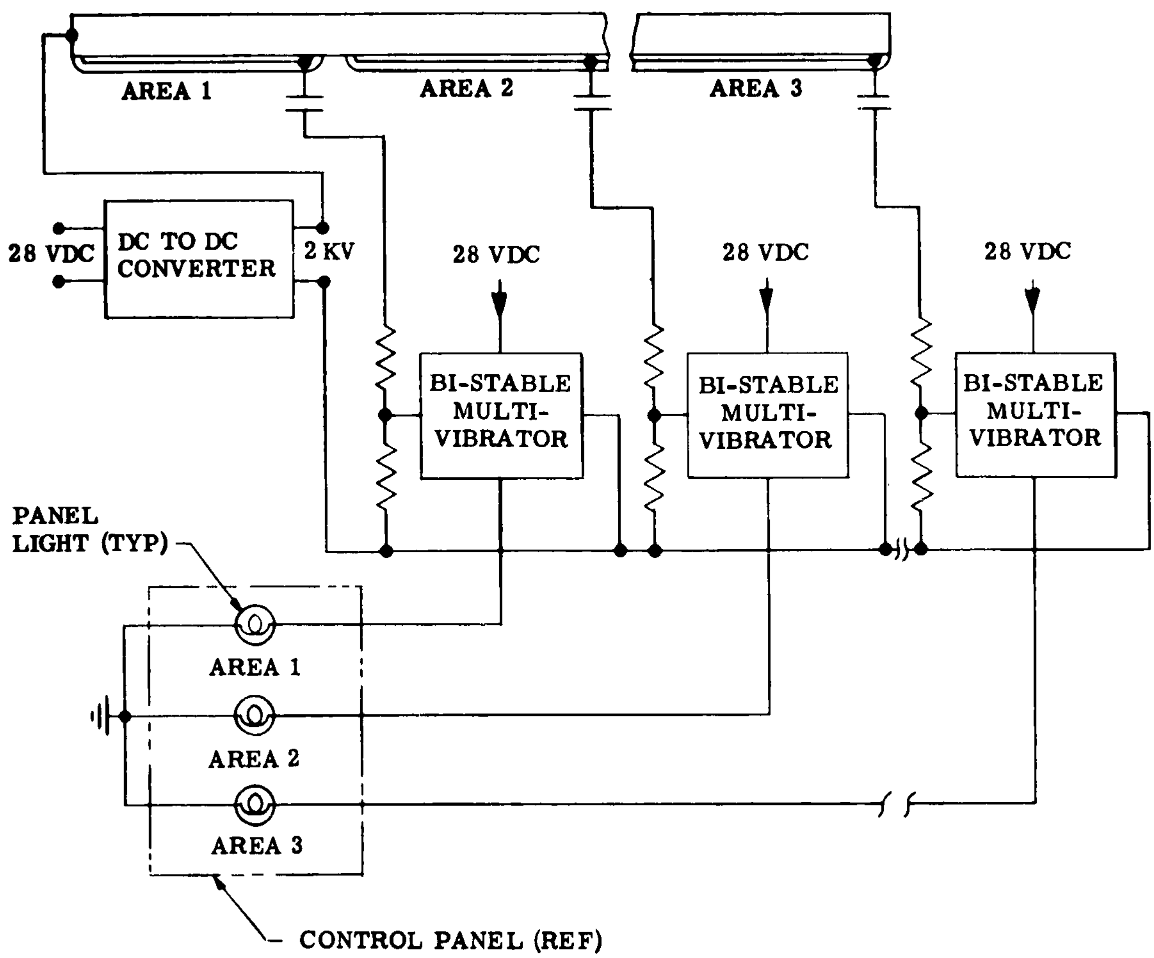
This method shares the disadvantage of the first method in that all fastenings must be insulated from the potential carrying aluminum. The problem is, perhaps, aggravated in this case since high voltages, on the order of 2000 volts, are required. Also, in this latter system, more electronic circuitry is required to the detection and warning system because the indicating current will be a pulse, rather than continuous.

4.3.5 Leak Detection and Location by Ultrasonics

Ultrasonic inspection techniques can be applied to a space cabin to detect punctures (i.e., flaws in the cabin pressure wall). The basic concept of this is shown in Figure 43. The radiator, a piezoelectric crystal, produces ultrasonic waves in the wall, which travel through the wall and are picked up by the receiver, which is



BASIC DETECTOR CONCEPT



ELECTRICAL SCHEMATIC

Figure 42. Continuity Sensor - Capacitor

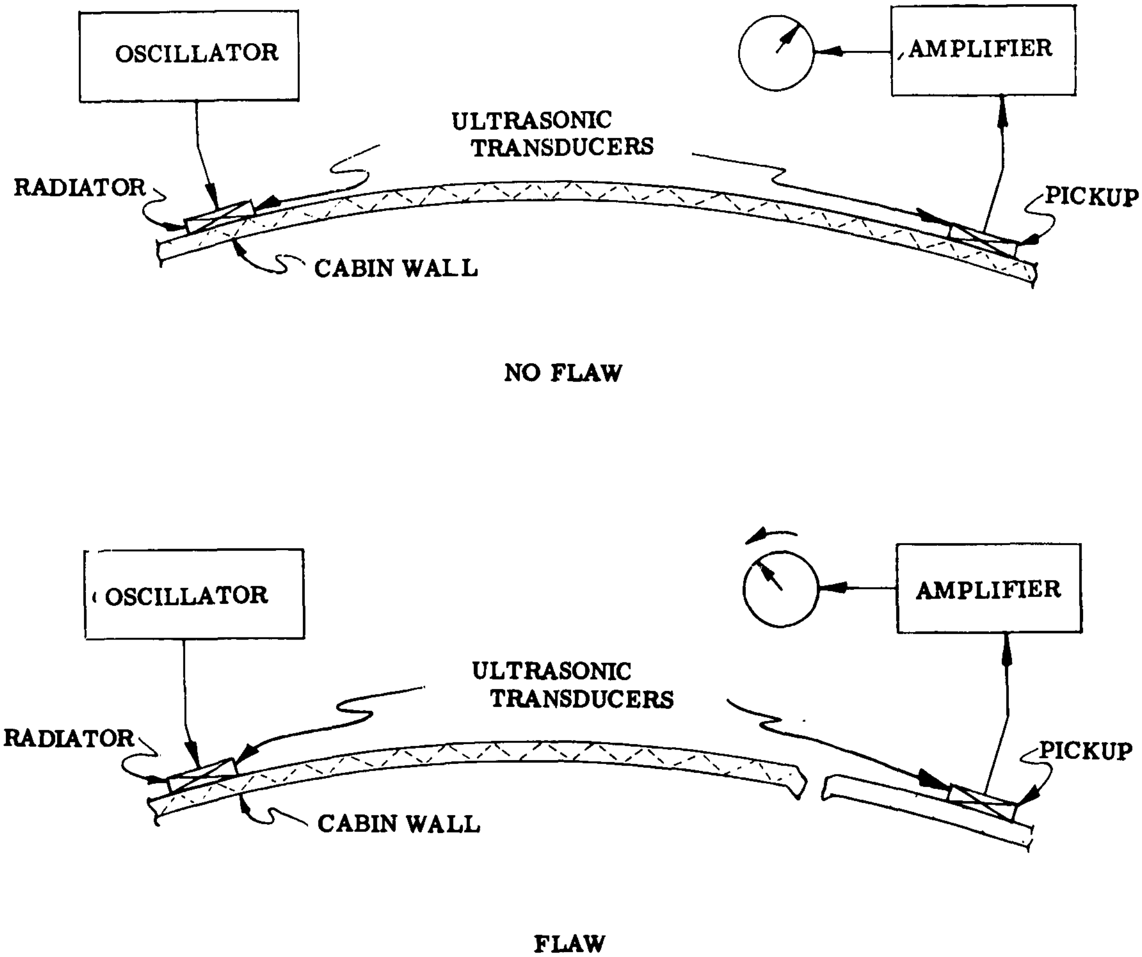


Figure 43. Continuous Wave Ultrasonic Flaw Detector

another piezoelectric crystal. As long as nothing interferes with the sound waves, the receiver will produce a nominal voltage. If a puncture occurs, or a flaw in the metal is produced between the radiator and receiver, it will block part or all of the sound waves from reaching the pickup.' The output voltage of the receiver will show a corresponding drop, which can be used to signal the warning system. Location of the leak would not be known precisely, but the general location could be determined by this method.

A pulse-echo technique can also be utilized. In this method, the radiator acts both to produce the sound waves, and receive the echo, or return signal, similar to a radar signal. (A separate pickup can also be used.) The radiator transmits a pulse of ultrasonic energy through the wall. Any defect or puncture will reflect, part of this signal back to the radiator. The radiator at this point acts as a pickup for the echo return. The output, displayed on a CRT oscilloscope, indicates the existence of a defect and the distance from the crystal transducer to the defect. Thus the defect may be precisely located, at the expense of the added electronic equipment required for the pulse-echo system. The pulse-echo system concept is shown in Figure 44.

In this pulse technique, the amount of reflected energy depends on the relation between the size of the reflecting surface and the wavelength at the particular frequency being used, the higher this ratio, the more energy will be reflected. Thus it is desirable to use high frequencies (short wavelengths) to detect the smallest flaws. For the continuous wave technique, high frequencies are desirable, since the more energy that is reflected, the greater will be the drop in signal strength from the receiver.

There is an upper limit to the frequency that can be used, however, which occurs when the grain boundaries in the material interfere (i. e., attenuate and reflect) with the ultrasonic sound waves. For fine, homogeneous structures such as aluminum or steel, it would be advisable to use a 5 MC frequency which will detect small punctures and flaws and not be affected by the grain boundaries of the material. On the other hand, for a very coarse structure, on the order of brass or bronze, the frequency must be lowered to 1/2 to 1 MC in order to pass the grain boundaries.

A low power (1, 000 volts peak to peak, 2-μ sec pulse) pulsed ultrasonic detector could detect flaws, or punctures in an aluminum cabin wall up to 25 feet away from the detector, if the flaw is above a certain minimum size. This minimum size is about equivalent to a 0.040 dia. hole, 1/8 inch long. Below this size the detection capability depends on distance from the detector. In this case the absolute minimum diameter flaw that can be detected is roughly 0.1% of the traversed distance of the sound wave. Thus, a 0.010 inch dia. hole could be detected from a distance of about 10 inches.

For the continuous wave system, the minimum puncture size detectable would be on the order of 0.040 inch dia. at a 6 ft. distance, and 0.075

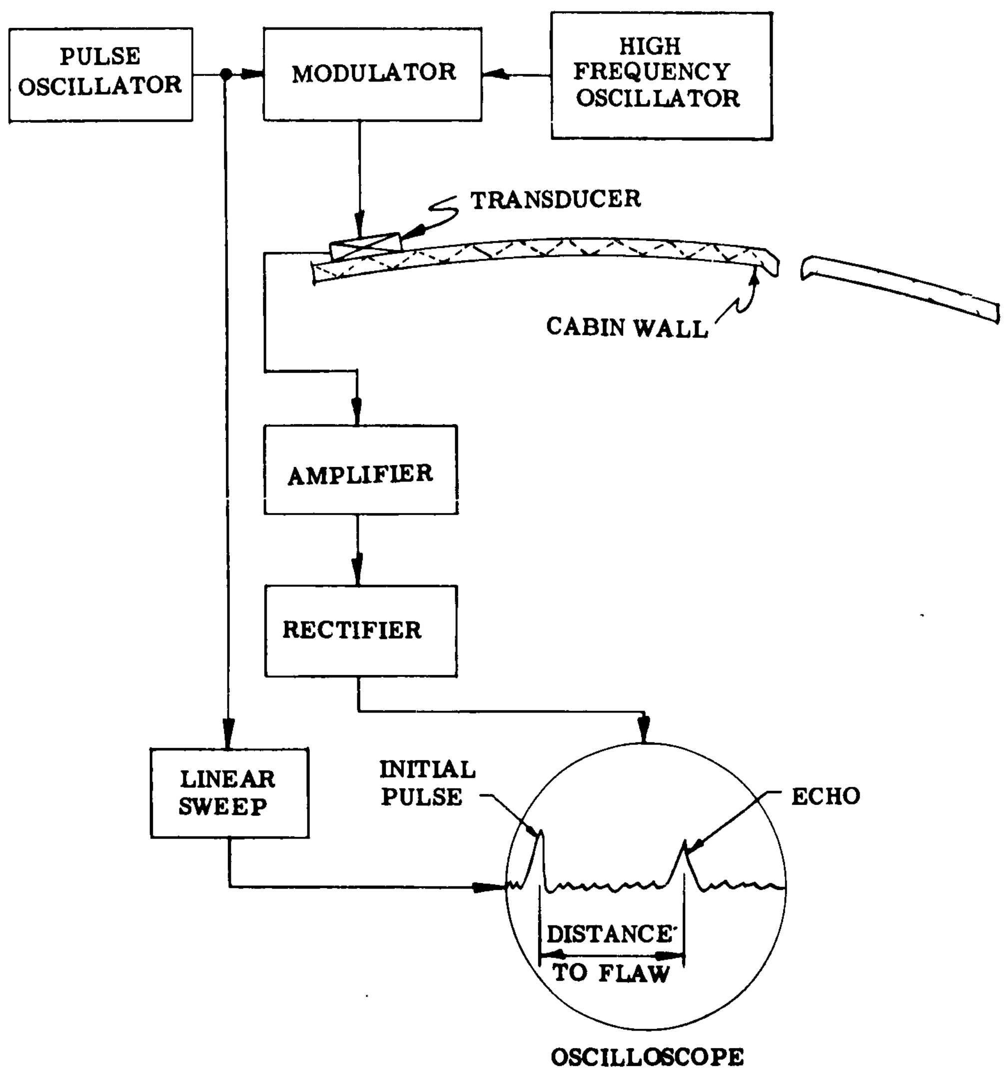


Figure 44. Pulse-Echo Ultrasonic Flaw Detector

inch dia. at about 25 ft. distance. For meteoroid puncture, these detection capabilities are within reason, because of the cratering phenomena associated with hypervelocity impact. Even a small meteoroid that just punctures the wall would leave a relatively large crater compared to the size of the orifice, or hole. A crack that penetrates the wall should be easily detected because of the relatively large cross-sectional area presented for reflection of the sound wave.

Implementation of the ultrasonic leak detectors into an overall system that would cover the entire vehicle wall area is, perhaps, the most undesirable aspect of this system because of the complexity involved. Considering the continuous wave method, the area covered by a single transmitting transducer and receiving pickup would be a strip about 1 to 2 inches wide, corresponding to the width of the transducer crystal. Thus a great many transducers are required to cover the entire cabin wall. In addition, if a connector, or any other discontinuity, such as a hatch or porthole, exists between the transmitter and receiver, it would block or shade the area extending behind it from the sound waves. In order to obtain coverage of these areas, more transducers are required. Fortunately, high quality welds, as are used in the cabin wall, would pass the ultrasonic sound waves so that no shading effect would be realized from them.

The number of transducers can be reduced if the transmitter and receiver are made mobile, that is, mechanized to travel along the wall. This may be quite difficult, however, due to interference with the structure, stringers, longerons, frames, etc. as well as cables, hatches, insulation, etc., that will exist between the cabin wall and outer wall of the space vehicle.

Use of the pulse echo technique would eliminate the separate pickup transducers required in the continuous wave method. However, the electronic complexity is increased, and the output of each transducer has to be displayed on an oscilloscope and the results interpreted by a crew member. This could be quite time consuming. On the other hand, the continuous wave system receivers produce a voltage which can be monitored automatically, and any drop below normal would automatically trigger the warning system. For these reasons, relative simplicity and ease of automation, the continuous wave system is best.

Each transmitting transducer and associated pickup receiver would be commutated to a single transmitting and receiving system. This would provide sequential operation of the system. Comparative voltages would be provided for each pickup and the warning system would display the exact set of transducers affected. Location of the puncture, or flaw, would then be confined to the band, 1 inch to 2 inches wide lying between the particular sending and receiving crystals. The system concept is shown in Figure 45.

Another method of utilizing ultrasonics would be to install acoustical pickups in the cabin wall to detect the sound of the air escaping from

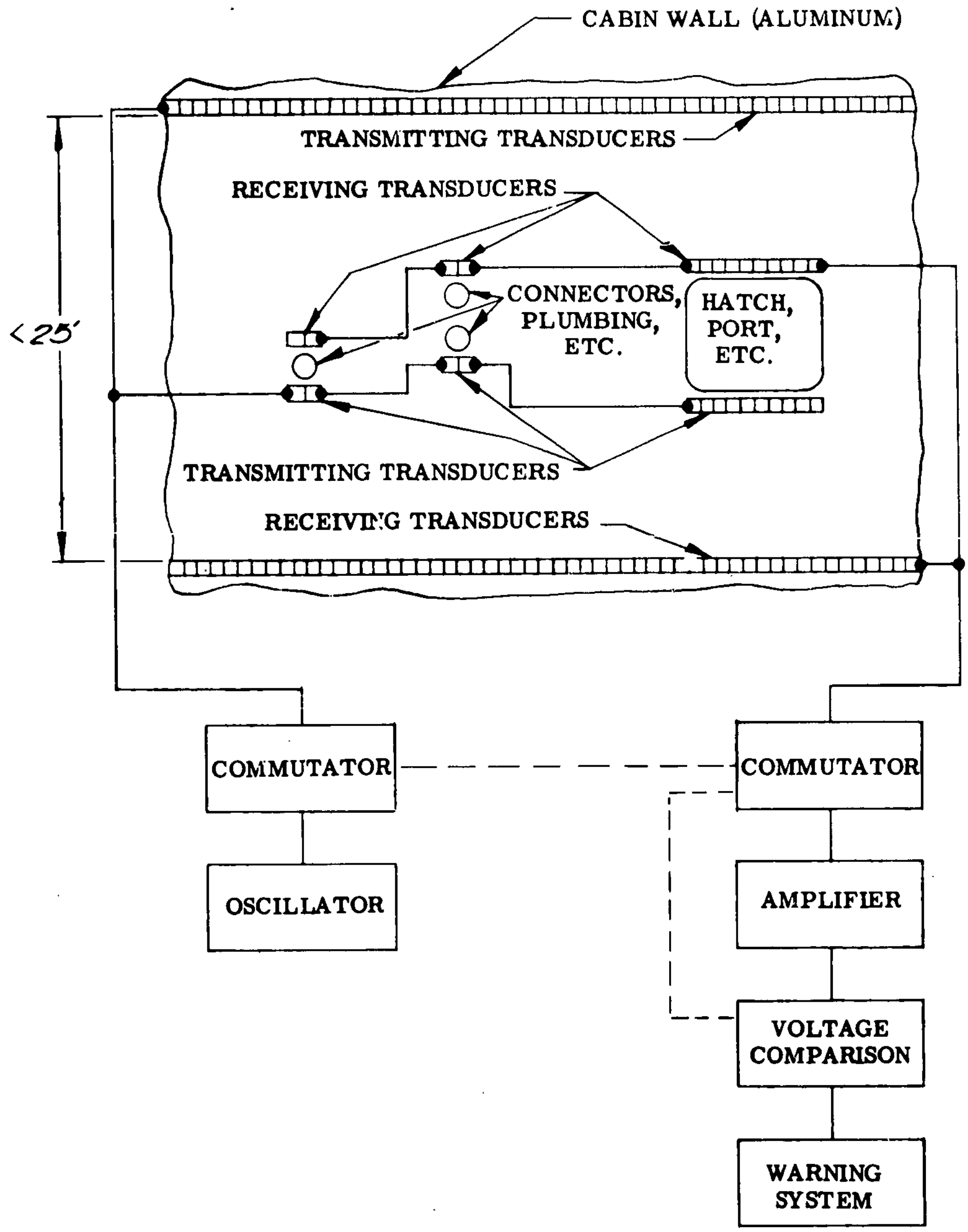


Figure 45. Comparative Transducers Detector System Concept

the leak. This sound would be transmitted from the leak to the detector through the wall. The feasibility of this concept, illustrated by Figure 46, rests on two parameters. One is the sound intensity in the wall, as a function of the size of the leak, and distance from the leak. This would have to be compared with the usable minimum response of the detector transducer in order to fix the maximum distance that the transducer can be located from the leak. The other parameter is the ability of the transducer system to distinguish between sounds produced by leakage, and other noises produced by equipment and/or men.

Values for either parameter are not known at this time and a laboratory program would be required to establish them. If it is found that there are combinations of sound frequencies, either ultrasonic or audible, that are characteristic of air leakage, and no other type of expected noise, then it is possible to install filters in the output of the pickup transducer so that noise other than air leakage would not trigger the warning system. It may be necessary to use a time delay, so that spurious sound pulses would not trigger the system. That is, sound waves, of the proper frequency, would have to be produced for a certain length of time in a steady amount before warning would be given. The human ear can be used for discrimination of sounds. If a sufficiently wide range transducer is used as the detector, the output could be coupled to an audio speaker or earphones. When a warning signal is given, the crew could listen to the output and determine whether it is the hiss of escaping air or another type of noise, from equipment for example, that may have tripped the warning system.

Another type of detector that utilizes the sound of the escaping air is the Ultrasonic Translator, Model 114 manufactured by the Delcon Corporation (see Figure 47). This unit utilizes a directional probe, housing the detector transducer, to quickly detect and locate leaks in pressure systems. Because of the directionality involved, the unit would be better suited for locating existing leaks than detecting leaks as they occur. It can be used for detection, however, by periodically scanning the cabin wall with the probe. The translator responds to molecular bombardment of the gas molecules as they escape through leaks. It picks up sounds in the 35, 000 to 40, 000 cps range and converts them to audible frequency (300 - 7000 cps). Noises sound as they are; therefore, the hiss of gas escaping could be easily distinguished from other noises. The sound waves of course, travel from the leak to the transducer through the intervening atmosphere.

Most of the information and the majority of applications for this Ultrasonic Translator have been concerned with the detection and location of leaks in pressurized systems, where the operator and detector would be located on the low pressure, or downstream side, of the leak. The detector is then sensing an "inrush" of air, or gas. The threshold of sensitivity, in this case, for the detector is about 0.1 cc/sec (equivalent to 2 ft^3/week) and distance in feet at which the leak can be detected is about equal to twice the discharge rate

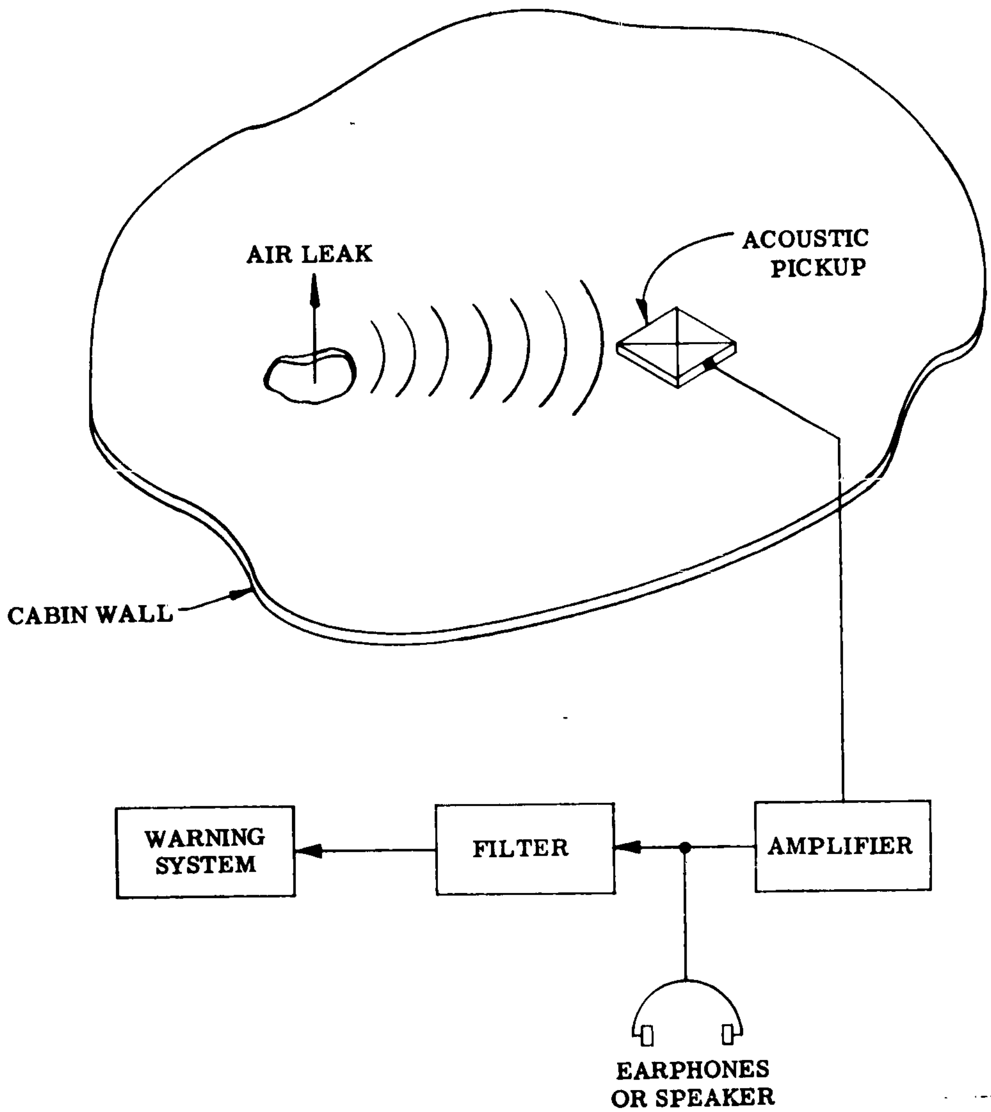


Figure 46. Acoustical Method of Leak Detection

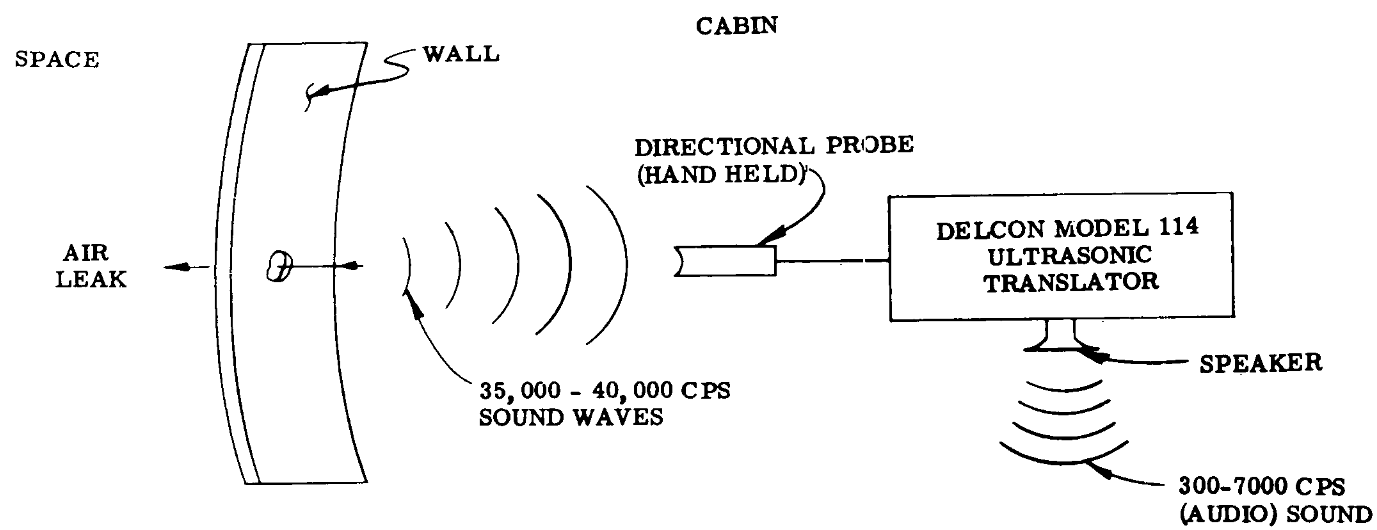


Figure 47. Ultrasonic Translator, Delcon Model 114 Leak Detecting and Locating System

in cc/sec. Thus the unit can detect an "inrushing" leak of 1.0 cc/sec (0.002 CFM) at a distance of 2 feet, and a leak of 5 cc/sec (0.01 CFM) at 10 feet.

In our case, however, the detector and operator would be located on the high pressure, or upstream side of the leak, and the air would be "outrushing" to a vacuum. The detection capability in this case is reduced because part of the sound would be "swallowed up" by the vacuum. The size leak vs. detection distance for these leaks to vacuum depends on the configuration involved (i.e., shape of orifice, wall thickness, cabin pressure, etc.) in a manner which is not presently known. Again testing and experimentation with the unit would have to be accomplished to establish the feasibility of this concept.

Both of these methods, acoustical pickups in the wall and the Delcon unit, if feasible would offer relatively simple means for detecting and/or locating leaks. It is desirable, therefore, to prove the feasibility of these concepts in the laboratory. For the former, the lab program should (1) analyze the sound spectrum of escaping gas to establish its similarities and differences from other noises; (2) measure transducer outputs as a function of the size of, and distance from, the leak; and (3) establish the feasibility of electrically filtering the transducer output so that the warning system is triggered only by leaks. For the Delcon ultrasonic translator, feasibility would be established by testing the unit against various vacuum leak configurations, varying in size, shape, wall thickness, cabin pressure, etc.

4.4 LEAK LOCATION

4.4.1 Inspection Methods

There are several methods used in industry for inspection of metallic parts for surface cracks or pores. One of these is fluorescent penetrant inspection. This is a sensitive way to detect minute cracks invisible to the naked eye. The procedure used in industry is to apply the fluorescent liquid penetrant over the surface to be tested, allowing it to enter any pores or cracks. The excess penetrant is then removed and the test piece is viewed under ultraviolet (black) light. Then the penetrant seeping back from the cracks fluoresces and clearly shows the defects in the part. Indications are brilliant; lines indicate cracks and dots indicate pores. A powdery developer which acts as a blotter is also usually used to aid the penetrant to emerge from the cracks. Seepage from cracks can also be assisted by moderate heating of the surface.

The materials most commonly used are an oil base, water-emulsifiable penetrant, the excess of which is washed off with a forced spray of water. Another type of penetrant is an oil base without emulsifier, in which case the excess is removed by a solvent. The developer can be a dry powder which is dusted over the surface after excess penetrant is removed and surface dried, or a colloidal suspension of

powdery materials which, when applied after the removal of the excess penetrant, is dried into a film by heating. When discontinuities are large or wide open, no developer is needed.

When this inspection method is applied to the problem of locating minute cracks or holes in a space vehicle cabin wall, through which gas is leaking, the best procedure appears to be the following:

First, the general location of the leak must be known and the surface cleaned of particles that could keep and hold the penetrant. Second, the penetrant must be applied by a brush type applicator complete with penetrant reservoir in a thin, even coat. Third, since a forced water spray is out of the question, the excess penetrant can be removed with a wet or solvent soaked sponge. Fourth, a developing powder in a colloidal suspension should be applied to the surface; a plain powder should be avoided because it would contaminate the cabin with dust. Fifth, the developer can be dried into a film by applying heat from a warm air blower. Sixth, the surface would be viewed under an ultraviolet light. Some exclusion of normal light is necessary, but usually just the shadow from the man blocking the light is sufficient. This entire sequence would take about thirty minutes in a one-g environment.

Some problems would exist. Since the crack or hole that is the object for detection is continuous through the wall, some penetrant would leak through to the vacuum, or space side of wall. This would be enhanced by the pressure differential also. Some penetrant will probably volatilize because of the vacuum, too. The point is that there will most likely be less penetrant available to re-emerge from the crack under the action of the developer "blotter" than is the case in the normal industrial inspection process. Because of this, the time between which the excess penetrant is removed and developer added and dried should be as short as practical. This may necessitate inspecting small areas at a time.

Another type of inspection method utilizes a colored penetrant, usually red, in a method similar to that above. In this case, however, ultraviolet light is not used, as the penetrant re-emerging from a crack would show a red line on the surface of the part under normal light. This method is not quite as sensitive as the fluorescent penetrant method, because the indication is not as brilliant.

Another method of crack detection is the magnetic particle technique or "Magnaflux" inspection. In this method, a magnetic field is established in the test object, magnetic particles are then applied to the surface, and the surface is examined for accumulations of these particles. The underlying theory is that magnetic poles exist around a crack in a magnetized surface because the flux lines, at this point, have to leave the metal and travel through the air. Magnetic particles will collect and adhere to these poles, trying to bridge the gap, but will not adhere anywhere else on the surface. Thus, if a magnetized surface is dusted with these magnetic particles, they will stick and outline any cracks or other defects in the surface of the part.

Because the space cabin walls will be made of non-magnetic material, a thin layer or sheet of magnetic material must be bonded to the inside of the wall in order to use this method. There apparently is no theoretical minimum gauge thickness of magnetic material that can be inspected by this technique. However, the thinner the section, the less magnetizing current can be carried, and the closer together must be the current supplying electrodes. This means that the area that can be inspected in a set time will be smaller for the thinner magnetic layers.

The magnetization of the wall surface can be provided by fastening two prods to the surface and supplying current through them to the wall. This will magnetize the surface with the lines of force running circularly around each prod. A yoke may be used instead of two prods. The yoke is a "U" shaped piece of ferromagnetic material with a magnetizing coil wrapped around the bottom of the "U". When placed on the wall, the lines of force run longitudinally from one point of the U to the other. The magnetizing current should be about 600 -800 amperes for each linear inch of thickness of the magnetic wall material. Distance between the prods or points of the U also depends on the current used. Either A. C. or D. C. current can be used but it is easier to demagnetize the material when A. C. is utilized. The direction of the magnetic field must be varied, also, because cracks running parallel within 45 degrees of the lines of force would not be detected. Thus the field should be shifted 90 degrees for each area.

Magnetic particles, gently applied over the surface in a cloud would not be practical in a space cabin in zero-g. The particles could be applied suspended in a liquid, either water or oil. In this liquid, they would be free to migrate to the cracks and crevices. The particles also could be suspended in a thin packet and moved over the wall by hand. The side next to the wall should be as thin as possible in order to get the particles close to the wall and the maximum flux. A sheet of mylar or other plastic film may suffice. The other side could be plexiglass or other suitable rigid, transparent plastic. Figure 48 shows the overall concept. The particles should be colored to contrast with the background. They can even be fluorescent and show up vividly under black light. Zero-g should enhance the ability of the particles to drift, in a free floating manner, to the lines of maximum flux (i. e., over a crack).

There are several types of coatings that can be applied to the interior surface of the cabin wall that would indicate the location of small punctures. One such type is a brittle coating such as "stresscoat". This is commonly used to analyze the strain existing in a part under load. The coating is sprayed on the surface and allowed to cure into a relatively hard, brittle coat about .003 to .005 inches thick. When the piece is under load, the coating will crack at a particular level of strain. For the case of detecting punctures, the strain sensitivity should be set at the yield point or slightly above to avoid erroneous cracking from normal loads. For aluminum alloy 6061-T6, this would be about 3600 μin./in. Present formulations, however, used in industry, crack at strain levels of

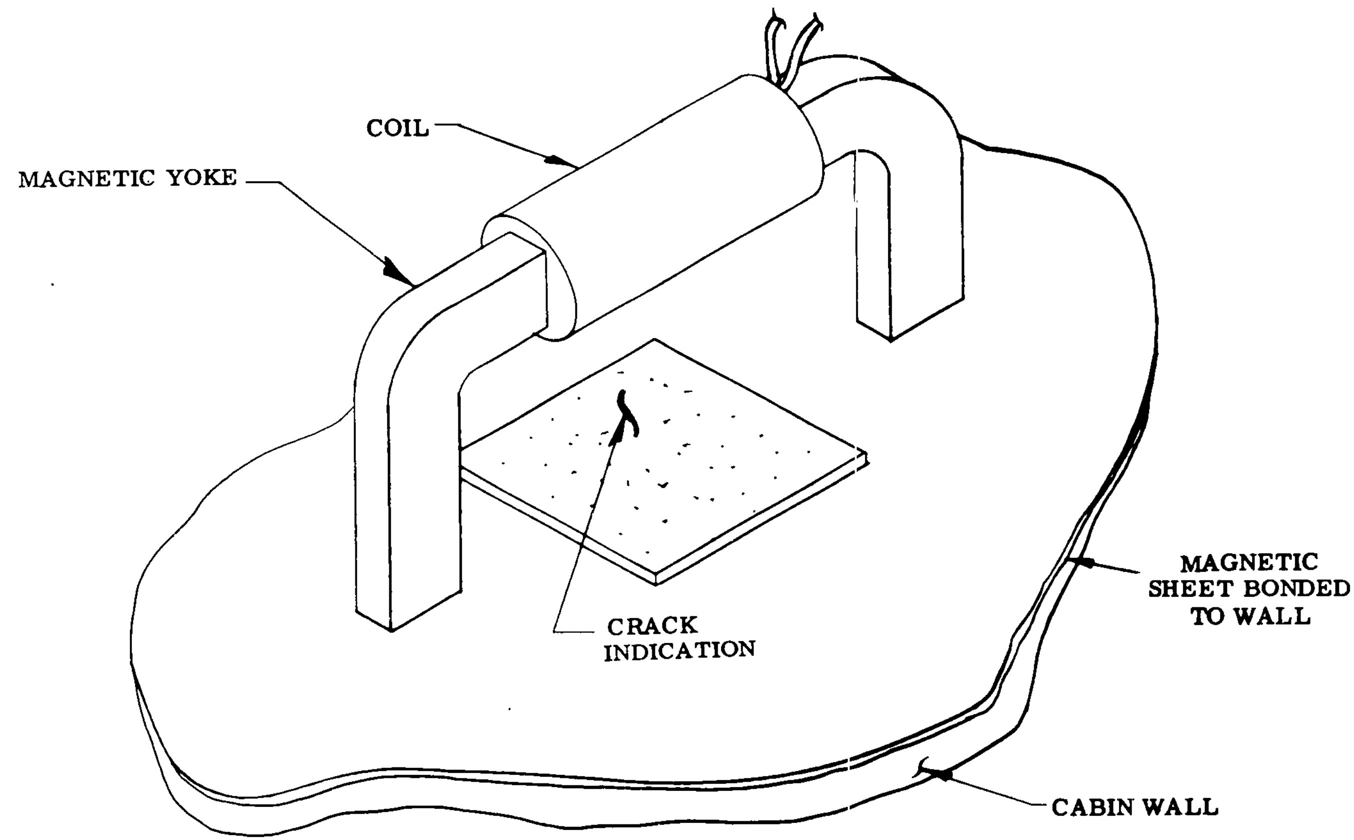


Figure 48. Magneflux Inspection

about 800 μin./in, corresponding to a stress of about 8000 psi in aluminum. This is too high a sensitivity since normal loads would induce cracking of the coating, and thus make it difficult or impossible to identify the cracks caused by punctures.

Additional disadvantages of stresscoat, for use as a means of locating punctures, are that it is sensitive to humidity and temperature and is easily scratched. Changes in humidity affect the strain sensitivity. Also, in commercial use, the ambient temperature is not allowed to drop below the temperature at which the coating was applied and cured, because if it does, the coating will crack. Scratches in the surface, caused by the normal wear and tear involved in handling, launching etc. of the cabin would also tend to nullify its principal objective. Also, stresscoat is not intended to last for a particularly long time. For the above enumerated reasons stresscoat is not very practical for our purposes.

Another type of coating that may be applied to the cabin wall surface is called "Photostress". This is a thin plastic sheet which, when bonded to the wall, would undergo the same deformation as the wall. Under strain, this material becomes doubly refracting (birefringent) so that when white polarized light is passed through it, colored patterns are observed. The amount of birefringence of this material is directly proportional to the strain. If the plastic is backed up by a reflecting surface, birefringence can be observed with a reflection polariscope.

In effect, use of this coating is equivalent to having an indefinite number of strain gauges, with virtually zero length, uniformly distributed over the surface. The plastic can be used over long periods, and has been used for checking such structures as bridges, dams, aircraft and missiles. It can also be used to obtain information on the plastic deformations encountered in yielding, and it therefore shows promise in locating punctures, since these plastic strains would be left in the cabin wall after the puncture and the loading has occurred. In order to obtain the maximum area of birefringence associated with a puncture, it is desirable to have the first "fringe" occur at the yield point of the wall material. This would eliminate unnecessary fringes occurring from normal loads in the walls (if the plastic film were more sensitive) and allow the thinnest coating to be used that would show the "gross" effect required. It should be noted also, that the area of plastic deformation associated with a puncture will be considerably larger than the hole created, particularly for small punctures. In addition, if sufficient heat is generated (on the order of 500°F) by the impact, the plastic film will deform and show an even wider area of birefringence, all of which adds up to making this area easier to locate.

For aluminum alloy 6061-T6, the yield stress is about 36,000 psi, which corresponds to a strain of 3600 μin/in or 0.36%. For the plastic film to show the first fringe at this value requires a thickness of about 1/32 in. For a 1000 ft^3 spherical cabin, this requires approximately 94.5 lbs. of material. Reducing the thickness by one-half also halves the weight, of course; but this also reduces the observable birefringent area since about 0.7% strain levels are required to produce the first fringe.

V. SYSTEM SELECTION

5.1 INTRODUCTION

As discussed in the preceding sections, there are a variety of methods that show possibilities for use in detecting, locating and repairing leaks in a manned space vehicle cabin. The task at hand is to select the optimum method or methods, or those that show the most promise for eventual development. To do this, the proposed techniques for leak detection, location and repair will be compared with respect to their ability to meet the requirements of the system. It becomes evident that to obtain a valid comparison between the different methods, the methods will have to be compared with reference to specific vehicles. This is because many of the parameters of the leak detection, location and repair system, such as weight, volume and power requirements, depend upon vehicle parameters, such as volume, mission duration, etc. Therefore, two different sets of vehicle parameters will be assumed in order to provide the reference required for systems comparison.

Vehicle number one is a three-man, earth-orbiting or lunar-orbiting spacecraft of modest size and mission duration. Vehicle number two is a space station of relatively large volume and mission duration. The parameters for each vehicle are listed in Table 7. Values listed are representative of those evolved from various GE-MSD studies of manned space vehicles to date.

TABLE 7. PARAMETERS FOR THREE-MAN, EARTH-ORBITING OR LUNAR-ORBITING SPACECRAFT OF MODEST SIZE AND MISSION DURATION (VEHICLE #1), AND SPACE STATION OF RELATIVELY LARGE VOLUME AND MISSION DURATION (VEHICLE #2)

PARAMETER	VEHICLE #1	VEHICLE #2
Crew Size (No. of men)	3	8
Mission duration (days)	14	60
Pressure vessel, volume, excluding airlock, (ft^3)	390	5700
Surface area of pressure vessel(s), including airlock (ft^2)	310	3500
Nom. cabin pressure (mm Hg)	360	360
(psi)	7.0	7.0
Nom. O_2 partial pressure (mm Hg)	180	180
Nom. N_2 partial pressure (mm Hg)	170	170
Estimated cabin leakage		
(cc/min)	1000	4000
(ft^3/min)	.035	.14
(lbs/hr)	.079	.31
O_2 (lbs/hr)	.045	.18
N_2 (lbs/hr)	.034	.13
No. of compartments (excluding airlock)	1	4

Before discussing the various methods of leak repair, a number of parameters must be established in order to recognize the mode of operation that will be followed. First, if the leak is very large, the first concern will be to get the crew into suitable secondary pressure protection. For vehicle #1, which has one pressure cabin, this would mean donning pressure suits. For vehicle #2, a compartmented vehicle with several pressure cabins, this means getting the crew out of the damaged compartment, into the safe compartment and closing the hatch between the two compartments. This would be the mode of operation whenever decompression resulting from a leak has the remotest chance of reaching the danger point of hypoxia or aeroembolism before the leak can be repaired.

The cabin could remain pressurized. This would be accomplished if the atmosphere control system were supplying gases at the same rate at which they are escaping. For large leaks this results in a severe weight penalty, besides imposing a severe requirement on the O_2-N_2 supply system. Figures 49 and 50 show the weight of atmospheric gases that would be lost for different hole sizes versus time, for cabins of 390 ft^3 and 1425 ft^3, respectively, if the cabin pressure were kept constant. Also shown, for the same hole sizes, is the atmosphere that would be lost if the cabin were allowed to decompress (i. e., no make-up O_2 or N_2 were admitted to the cabin). Decompression up to the dashed line could be tolerated by the crew with no secondary pressure protection, and corresponds to a cabin pressure of 3. 5 psia. Decompression beyond the dashed line could not be tolerated by the crew unless suitably protected. Note that for the larger holes, the difference in weight loss between holding a constant cabin pressure, and allowing decompression becomes significant in a very short time.

Thus, looking at Figure 49, if a reasonably safe time limit for repairing a leak were 20 minutes, then, for punctures less than 0. 25 inch dia equivalent, the crew should repair the leak directly. There would be no requirement to don pressure suits first, as the weight lost in maintaining the cabin pressure is only slightly more than if the cabin decompressed. This difference would most likely be cancelled, because of the additional time required to don the suits, which has to be added to the time for repair. On the other hand, for punctures greater than 0. 25 inch dia equivalent, the crew should don pressure suits prior to repairing the leak. The difference in atmosphere lost, if the cabin remained pressurized, would amount to about 20 lbs. in 20 minutes time. Thus the dividing line between modes of operation in this case, will be set for leaks of . 25 inch equivalent diameter.

The second case, Figure 50, is a little more complicated. This is because, as the men retire to a different compartment to don pressure suits, the damaged compartment depressurizes. Then, when the hatch between compartments is opened for the men to return to repair the leak, the second compartment depressurizes. Thus, in effect, twice as much gas is lost in a cabin depressurization as

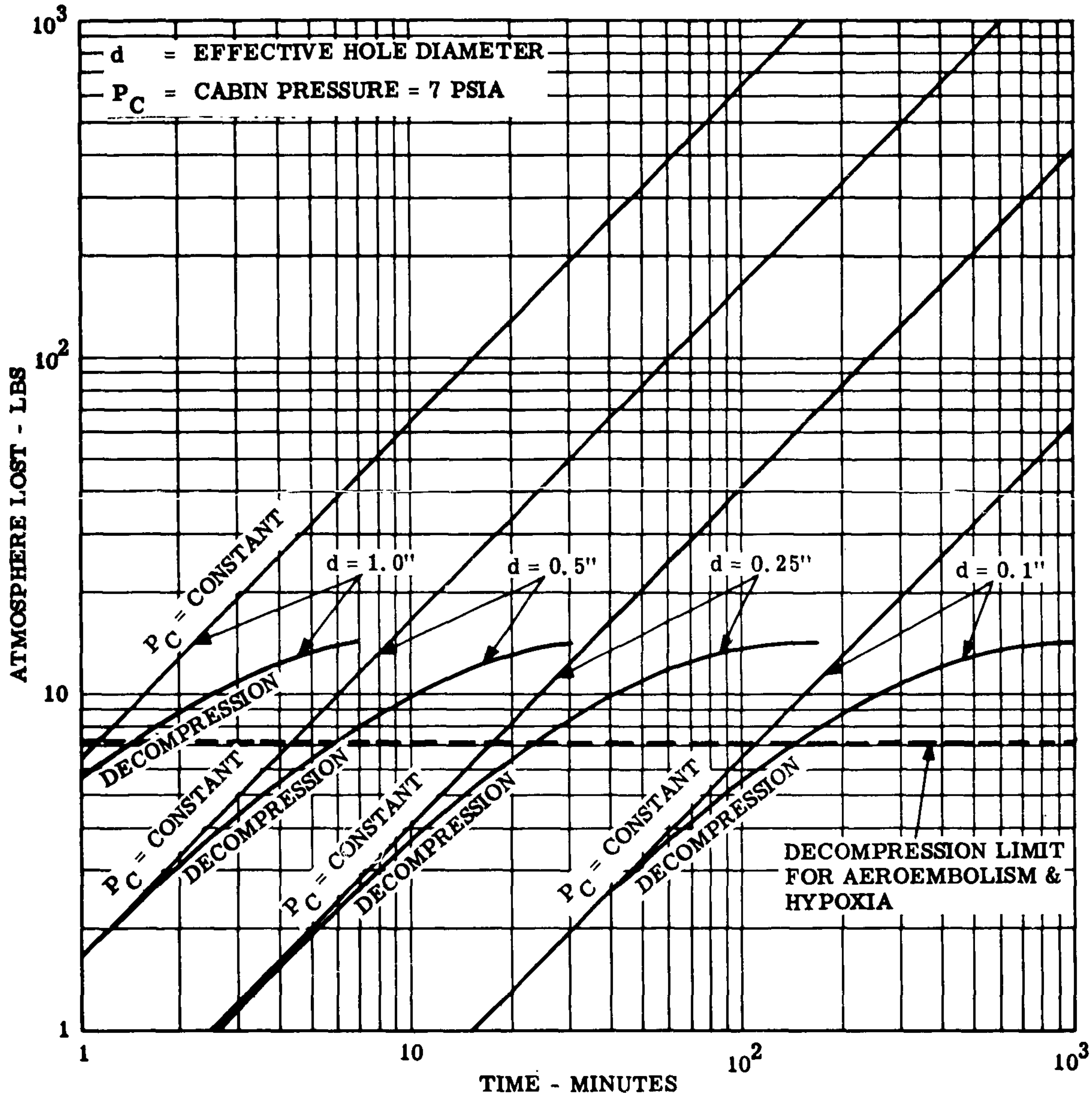


Figure 49. Atmosphere Lost Vs. Time for Repair (Cabin Volume = 390 ft^3)

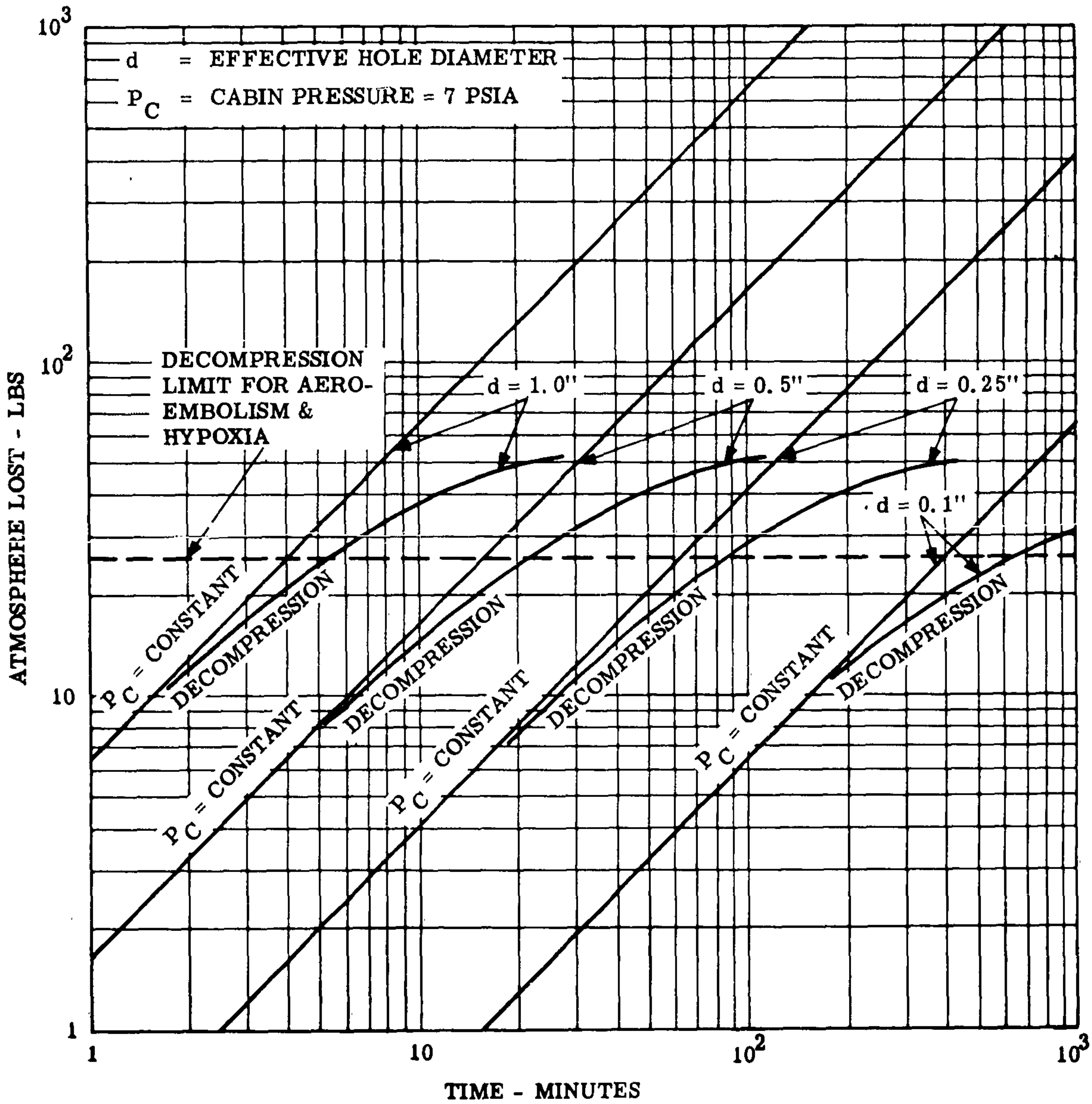


Figure 50. Atmosphere Lost Vs. Time for Repair (Cabin Volume = 1425 ft^3)

is shown on the curve. This does not have to occur if the men can don suits in the damaged compartment while it is depressurizing, or if there is an airlock between compartments. The former is hazardous from a safety standpoint, and the latter would occupy too much otherwise useful volume of the vehicle. Thus the dividing line between modes of operation is at about 0.9 inch equivalent diameter holes. At 1.0 inch diameter weight lost in depressurizing is about 100 lbs, and the weight lost in maintaining pressure is about 130 lbs. in 20 minutes, thus the trade-off point lies at slightly smaller diameters.

For the smaller vehicle, leaks larger than 0.25 inch equivalent diameter will be repaired with the cabin depressurized and the crew in pressure suits, while the same holds true for the larger vehicle for leaks greater than 0.9 inch equivalent diameter. In order to implement this system, the crew must know, almost simultaneously with the detection of a leak, if they must resort to secondary pressure protection, or may go ahead and repair the damage. Since the leak detection methods will not indicate the magnitude of the leak, another means must be used to provide this information. One logical way of accomplishing this would be as follows:

1. Following leak detector warning, atmosphere supply systems are closed.

2. Pressure drop in cabin is measured by total pressure aneroid gauge.

3. If pressure falls faster than a predetermined rate, warning is given to enter secondary pressure protection devices.

The above sequences would be automated and the system sequenced in this way each time a detector signals a leak. The entire system could be designed to activate the decompression warning in a matter of seconds. It is possible that better systems could be designed to provide this warning, but this consideration will be left for later development.

If the leak is smaller than the critical size, indicating repair while the cabin is pressurized, a further refinement is required in assessing the magnitude of the leak. That is, the crew must know if the leak is relatively large, requiring immediate attention and repair within the 20 minute time allotted, or if the leak is small, and should not take preference over other, more important duties. For example, suppose the crew were engaged in a rendezvous or other operation requiring their full attention, and a leakage alarm sounded. If no decompression warning were given at the same time, the crew would have to know whether to drop their present tasks to repair the damage, or pursue their task to completion and then repair the leak. Again, a system similar to the above for decompression warning could be developed to indicate the relative magnitude of the leak. However, a simple aural reception of the leakage noise

might suffice. That is, if the crew could hear the leak, it would indicate that the leak was large enough to require immediate attention. If it could not be heard, the repair of the leak would not take preference over other more important duties.

5.2 LEAK DETECTION SYSTEMS

The first criterion for comparison will be the system's ability to detect, locate and repair all types of leaks expected, or possible, in the space vehicle hull. Basically, the types of leaks can be classified into three categories as follows:

CATEGORY I - Relatively large punctures of the cabin wall (i. e., punctures large enough that decompression protection is the primary concern). Repair will be made with cabin depressurized and crew in pressure suits. Causes - meteoroid, internal fire or explosion, collision during rendezvous, hostile action.

CATEGORY II - Small punctures and cracks. Cabin remains pressurized and repair is made directly by crew. Causes - same as Category I plus abnormal stresses arising from propulsion system failure, vibrations from equipment, and random design failure.

CATEGORY III - Seal failures. Causes - failure of the seal material itself, or warping or movement of the seal surface flanges (or the seal) due to abnormal stresses, or random design failure.

Not all of the leak detection techniques could be used to detect all three categories of leaks, as some are only sensitive to an actual penetration of the hull. These techniques are biased toward the protection from leaks due to the meteoroid penetrations. However, the meteoroid puncture probability will have to be small, for additional reasons besides resultant leakage, because of the great danger a penetration would have for the crew. The so called "vaporific effect" possibility of explosion, damage to men and equipment from a spalled particles, etc., represent a greater hazard to the crew than the leakage aspect of meteoroid puncture, thus, through design, puncture probability will be very low.

From the standpoint of detecting all leakage, therefore, the techniques that are sensitive only to actual penetrations by a foreign object through the hull will have to be discarded in favor of the other methods of detection.

There are three methods that would detect all types of leaks, and which are sensitive to any atmosphere leakage. They are the pN_2 decay or N_2 utilization rate techniques, acoustic methods and ion gauge technique.

5.2.1 pN_2 Decay on N_2 Utilization Leak Detection Techniques

First, consider the method of detecting a leak by the pN_2 decay technique. This can be accomplished in several ways, as noted in the previous discussion, depending on the system used to supply make-up nitrogen to the cabin. If nitrogen is supplied by means of a total pressure demand regulator, operating independently of the nitrogen partial pressure, the procedure to determine the cabin leak rate would be as follows:

Turn off the N_2 makeup supply. Determine time for the nitrogen partial pressure to drop a set amount. Calculate leak rate.

If however, nitrogen is supplied in response to the nitrogen partial pressure by means of a valve that opens and closes at set values of pN_2, the time between closing and opening of the valve can be used to calculate the cabin leak rate. This is analogous to the first method, as it also measures the time for the pN_2 to drop a set amount; in either case, the parameters are the same.

It will be assumed that the equipment needed to measure pN_2 will already be aboard the vehicle, as part of the atmosphere sensing and control equipment. Thus this leak detection method should not be penalized by including the equipment weight. The measuring equipment could be either a mass spectrometer or a gas chromatograph. With either of these units, the best estimate of accuracy in measuring pN_2 at about 170 mm Hg is $\pm$ 2 mm Hg. This means, for example, in measuring a drop of 5mm Hg pN_2 (170 to 165 mm Hg) the error could be $\pm$2 mm Hg, or the actual drop could be between 3 and 7 mm Hg. Figure 51 shows the time for the pN_2 to fall 5mm Hg, with no makeup N_2 added, for a cabin of 390 ft^3 volume (Vehicle #1) versus the cabin leak rate.

The time duration required by either of these systems that depend on measuring directly the nitrogen partial pressure can be equated to a weight penalty. This weight penalty would be the weight of gases lost between initiation of the leak and detection of the leak. The maximum weight penalty would occur if the leak is initiated at the beginning of the cycle (i.e., when the N_2 supply shuts off). In this case, the maximum time elapses between leak initiation and detection. In addition, if the inaccuracies in measurement of the pN_2 are such that, for a reading of 5 mm-Hg ΔpN_2, an actual drop of 7 mm Hg pN_2 occurs, this time lapse, and the weight penalty will be further maximized.

In accordance with the above, the maximum weight penalty can be calculated. (The weight penalty will be independent of the leak rate since a fixed amount of atmosphere will escape for a set ΔpN_2. Of course, this means that a large leak will be detected sooner than a small leak.)

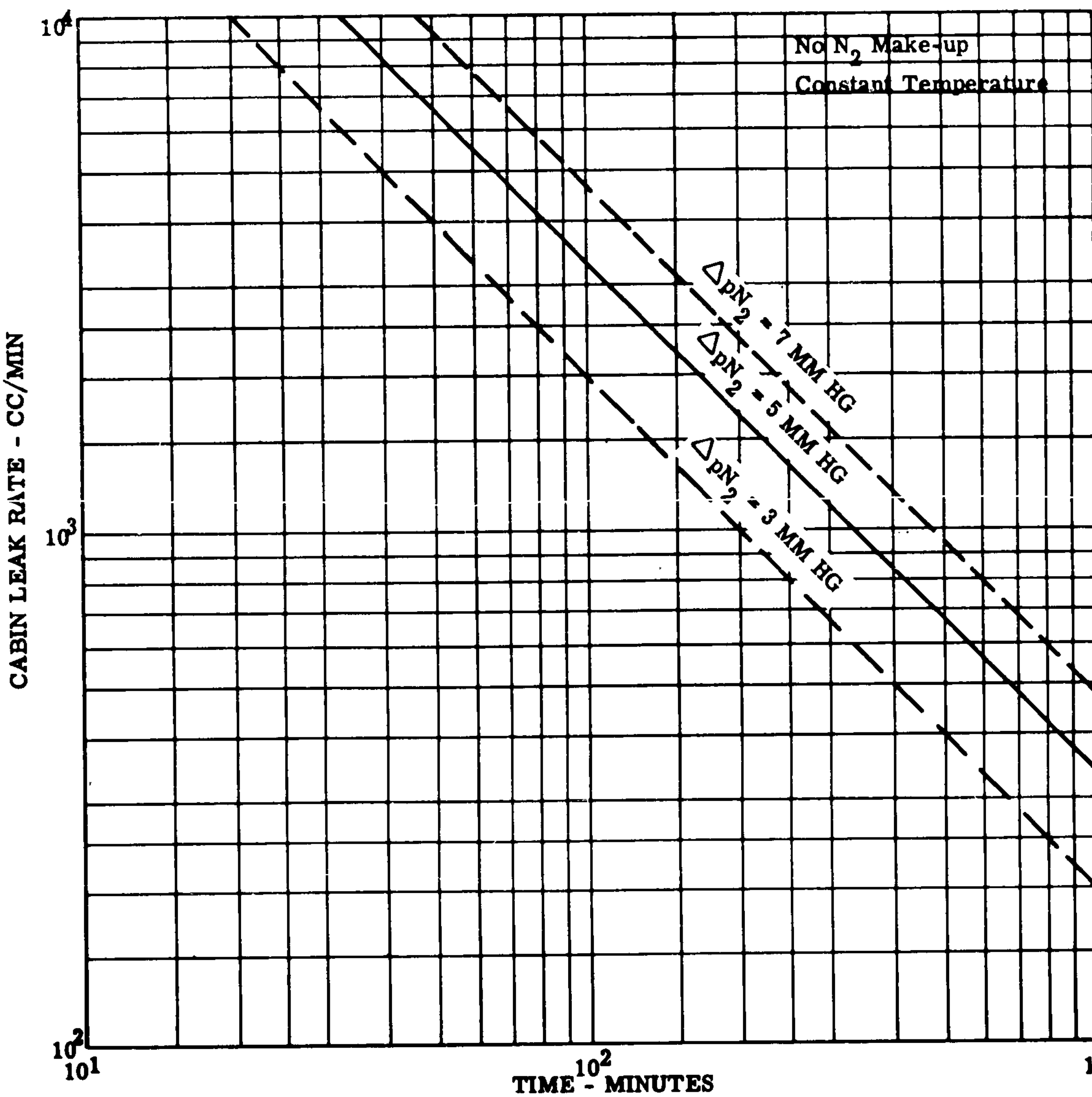


Figure 51. Time for Cabin pN_2 to Drop 5 mm Hg vs. Cabin Leak Rate

For Vehicle #1

$$W_t = 56,632 \frac{V}{t} \frac{(Po-P)}{Po+P} \text{ cc/min}$$

$$W_t t = (56,632)(390) \frac{(170-163)}{(170+163)} = (56,632)(390) \frac{(7)}{(333)}$$

$$W_t t = 465,000 \text{ cc}$$

weight loss $\cong$ (4.65) (.0353) (.0369) $\cong$ **0.606 lbs.**

For Vehicle #2

$$W_T t = (56,632)(7500) \frac{(7)}{333} = 6,790,000 \text{ cc}$$

weight loss $\cong$ (6,790) (.0353) (.0369) = **8.85 lbs.**

To arrive at a realistic weight penalty, these numbers should be multiplied by a factor to include the gas tank weight. This factor will be assumed as 1.5 so that, for each repairable leak for vehicle #1, the weight penalty is about 0.9 lb. and for Vehicle #2 is about 13 lbs.

In addition, these weights should be multiplied by the estimated number of individual repairable leaks that will be considered in the emergency requirements. For Vehicle #1, the number will be arbitrarily chosen as two, and likewise, for Vehicle #2, five. Thus, the total comes up to 1.8 lbs. for Vehicle #1, 65 lbs. for Vehicle #2.

As seen from Figure 51 with a +2 mm Hg error in reading pN_2, the calculated leak rate could vary +40% from the nominal. This means that, in order to obtain a significant increase in the calculated leak rate, the leak will have to be 80% above the normal established amount. For example, if the cabin were leaking at the maximum allowable amount of 1000 cc/min, and suddenly, another leak occurred, this leak would have to be at least 800 cc/min to insure being detected. Other errors, in addition to those in the measuring equipment, would be present also, such as changes in $_pCO_2$, $_pH_2O$ and $_pO_2$ during the time the Δ_pN_2 is being measured, which would increase this minimum detectable leak, so that perhaps, 1000 cc/min is a more reasonable value. This minimum detectable leak can be reduced by measuring a greater ΔpN_2, say 10 mm Hg, but first a look should be taken at locating the leaks using this detection system as there is a minimum leak which can be located.

This leak detection system will not give any indication of the location of the leak so that auxiliary leak location methods must be used. However, all the location methods except one, namely acoustic, depend on knowing at least the general location of the leak in the

cabin wall. It would be impractical to use these methods in any other situations since the cabin wall will not be readily accessible (i.e., equipment must be moved, flooring removed, etc.) If it is not known beforehand which equipment to move, it becomes a large, tedious, time consuming task to examine the entire interior surface of the wall.

The smallest equivalent diameter leak that could be located with an acoustical unit, such as the Delcon Ultrasonic Translator, from a practical distance of about 3 ft. would be about 0.055 inch diameter (cabin pressure 7 psia). This would create a cabin leak rate of 28.8 lbs/day or 15,320 cc/min. It is evident then that this system is limited as to the size of leak that can be located practically. This minimum leak, if multiplied by the mission duration, becomes an impressive weight penalty for this system amounting to 403 lbs. for Vehicle #1 and 1730 lbs. for Vehicle #2. This system would only be optimum if other proposed systems could not detect and locate smaller leaks with less system weight than the above figure.

It should be recognized that the minimum detectable leak, dependent on location techniques, could be reduced by examining the entire interior wall surface. Even visual inspection could detect leaks smaller than 0.055 inch equivalent diameter. As mentioned, however, this is impractical because it would be a time consuming process, and would take the crew away from other duties for an extended period. A tradeoff could be made, strictly on a weight basis, by estimating the length of time required to locate smaller leaks, and multiplying this time by the leak rate to determine weight loss, and comparing it to the above weight penalties. Unless it would take more than 14 days to locate a leak smaller than 0.055 inch diameter for Vehicle #1 and more than 60 for Vehicle #2, examining the entire wall would save weight. There has to be some time limit placed on the time allowed for this location. It is impractical to have the vehicle mission disrupted for such long times while the crew searches for the leak. Thus, this method of leak detection will be discarded in favor of other techniques, unless it is found that these other techniques are not appreciably better for detection and location.

Summary of Nitrogen Utilization Rate as a Means for Leak Detection

1. Minimum Detectable Leak - 1000 cc/min when measuring a ΔpN_2 of 5 mm Hg, less if a larger ΔpN_2 is measured; but longer time for detection is then required. Trade off involved between atmosphere lost during long time required for detection versus detection of smaller leaks. However, location more of a problem than detection.

2. Weight, Volume and Power Requirements - System requirements very low because of use of existing hardware. 7 lbs, 1/2 ft^3 needed for acoustic locator. Because of high minimum

leak, however, weight penalty becomes high, 400 lbs. for Vehicle #1, 1700 lbs. for Vehicle #2. Also add 1.8 lbs. for Vehicle #1, 65 lbs. for Vehicle #2 because of long detection time required.

3. Time for Detection and Location - Time for detection is long, for a 2000 cc/min leak rate, time for detection is about 2 hr. 45 min. for Vehicle #1, about 15.6 hours for Vehicle #2 to detect 5000 cc/min. Time for location with Delcon unit is reasonable compared with above times. Time for location by other methods becomes impractical because general location is not known.

4. Complexity and Reliability - System is simple, based on existing subsystems. Reliability will be equal to that for the atmosphere sensing and control system, which should be excellent.

5.2.2 Acoustic Leak Detection Methods

The second type of detection system would utilize acoustical pickups, located in the cabin wall to detect the sound of air escaping. As mentioned previously, the feasibility of this concept rests upon two parameters, both of which would require a laboratory test to establish. They are 1) sound intensity in the wall structure as a function of the size of the leak and distance from the leak, and 2) ability of the system to distinguish between normal sound and the sound of air escaping. If this system is feasible, it may have merit. The acoustic pickups would be quite small and lightweight as this design could take advantage of the similarity with phonograph pickups, miniature microphones and/or ultrasonic transducer crystals. Amplification should not be a problem either, and would use transistorized amplifiers and have low power requirements. Only one amplifier is required for the system as each detector can be commutated to the amplifier, thus providing sequential operation and identification of the detector affected by a leak.

To aid in locating the leak, a relatively large number of detectors can be used, each covering a small area. A somewhat larger number of detectors can be afforded for locating the leak than might be justified for strictly detecting the leak, because of their small size and weight. That is, increasing the number of detectors would, of course, increase the system weight, but the absolute magnitude of this increase would be small, and could be balanced by the gain in the leak location ability. The location of the leak can thus be indicated within a relatively small area. The crew would then know where to look, and what equipment to remove to further pinpoint the leak and repair it.

Summary of Acoustic Leak Detection

1. Minimum Detectable Leak Rate

   Unknown. Would be a function of transducer sensitivity vs. size of leak and distance from leak. Distance from leak could be kept quite small by using more transducers (closer spacing) with small absolute weight penalty.

2. Weight, Volume & Power Requirements

Small. Essential components of system would be small and lightweight and have low power requirements.

3. Time for Detection and Location

Some minimal amount of time needed between initiation of a leak and the warning signal in order to eliminate spurious sound pulses from triggering system. Time for location is short because leak would be located within small area automatically.

4. Complexity and Reliability

System would be fairly complex, requiring commutation, time delays, amplifiers, filters, etc. Reliability would, therefore, be lower but could probably be raised to very high values through redundancy with small weight increase.

5.2.3 Ion Gauge Leak Detection Technique

In the case of the third type of leak detection system, the ion gauge technique, more information is available because it is possible to estimate the pressure distribution that would occur outside the cabin wall as a result of a leak through the wall. Since the ion gauge is a pressure sensitive device of known sensitivity, these two facts can be related to yield the parameters of minimum size of leak vs. detector distance from leak. The estimate of minimum detectable leak versus detector distance from the leak for any detector sensitivity is as follows:

Most space vehicles presently planned will be of double wall construction, the inner wall forming the pressure cabin and the outer wall being a meteorite bumper or re-entry shield structure. The wall spacing will be assumed to be 4 inches. (In the actual vehicles, if the wall spacing is less, these results will be conservative, and if more than 4 inches, these results will be optimistic.) In addition, it will be assumed that any longerons or stringers do not materially impede the flow of gas leakage from expanding between the walls. Areas in the outer skins through which the gas can escape will be neglected since the area between the walls through which the gas can expand is so much greater. Then,

$P = n\,KT$ where n = no. of molecules/unit volume, $\frac{1}{cm^3}$

K = Boltzman Constant, dyne-cm/K

T = temperature, K

P = pressure, dynes/cm^2

Let Q = no. of molecules entering through leak/unit time, t (sec). In time dt, Q dt molecules have entered. The volume encompassing Q dt molecules at a distance r (cm) from leak

$$V = 4\pi\ (r + dr)^2 - 4\pi\ r^2, \quad cm^3$$

where dr = f (dt)

$$V = 4\pi\ (2r\ dr + dr^2) = 4\pi\ 2r\ dr, \ dr^2 \text{ is small}$$

Assume the molecules move at sonic velocity

Then, $dr = cdt$ (c = sonic velocity, cm/sec)

and $V = 8\pi r\ cdt$

now $n = \dfrac{Q\ dt}{8\pi\ r\ cdt}$

and $P = \dfrac{Q\ KT}{8\pi\ rc}$

Then, in terms of P in mm-Hg, ω in lbs/hr and r in feet, using the necessary conversion constants and values.

$$P = 1.2 \times 10^{-3} \ \frac{\omega}{r}$$

Figure 52 plots the above relationship for a leak detector sensitivity of 1×10^{-5} mm-Hg. Also shown, plotted against the minimum detectable leak rate, ω, is the coverage area, A, of each detector and the equivalent orifice diameter, d, of the leak. To estimate the best operating conditions for the detector system, from a weight standpoint, a trade-off can be made. This trade-off is shown in Figure 53 for the vehicle #1 and in Figure 54 for the vehicle #2.

The trade-off time, in these figures, is that time which, when multiplied by the minimum detectable leak rate, equals the weight of the leak detector system. In other words, it is the time, starting from the initiation of the minimum detectable leak, in which the leakage weight penalty (if not repaired) equals the weight of the system. The leak detector system weight was taken as 2 + .875 n lbs. where n = no. of detectors required. The leakage weight penalty was taken as the minimum detectable leak rate, w, times 1.5 to account for the gas storage system weight.

The other ordinate scales in Figure 53 and 54 are for convenience in interpreting the results. (The main plot is ω, lbs/hr, vs T, days.) For vehicle #1, with a mission duration of 14 days, it would not pay to detect leaks below 0.028 lbs/hr, because the trade-off time, at

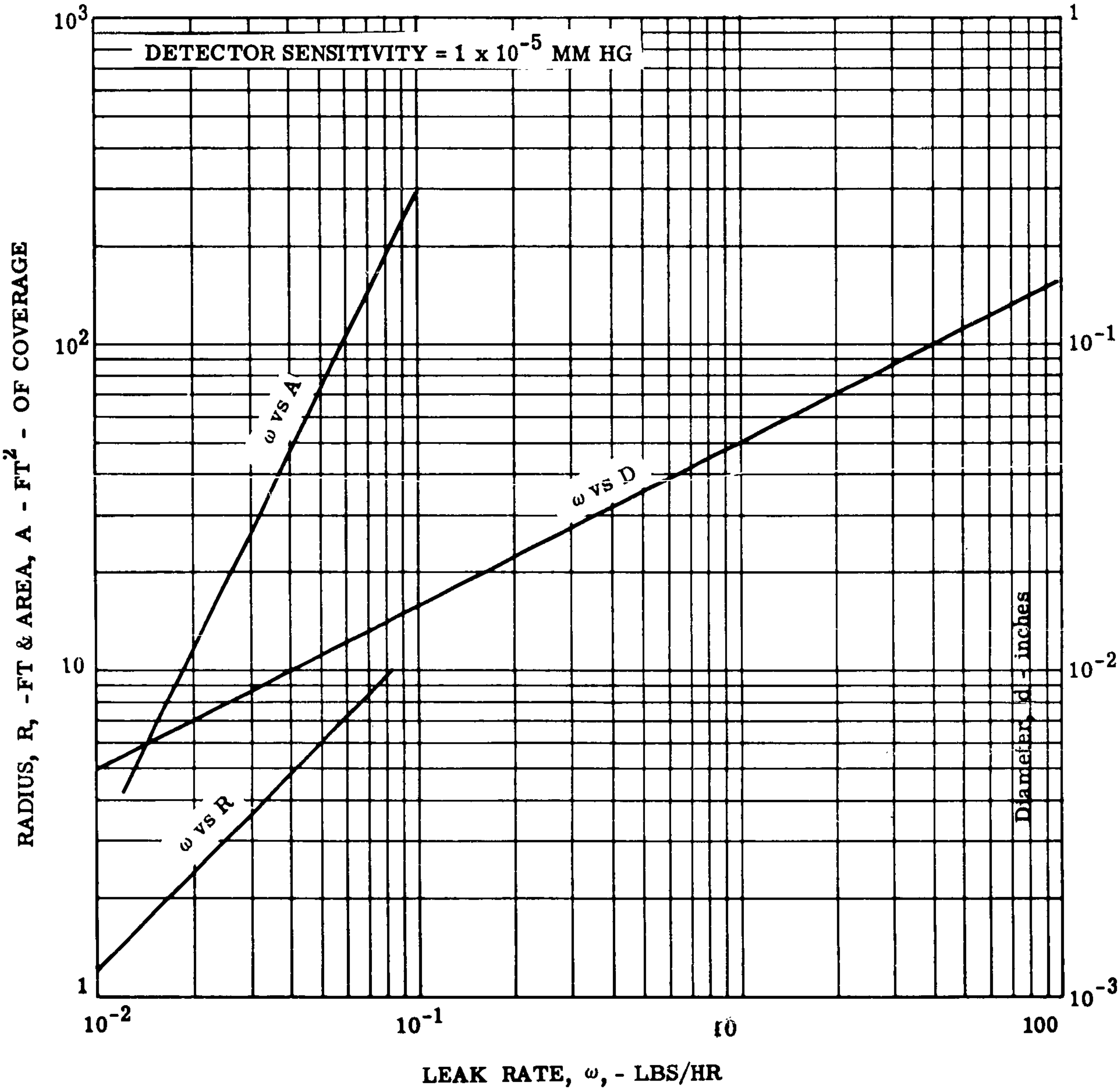


Figure 52. Ionization Gauge Leak Detector Parameters

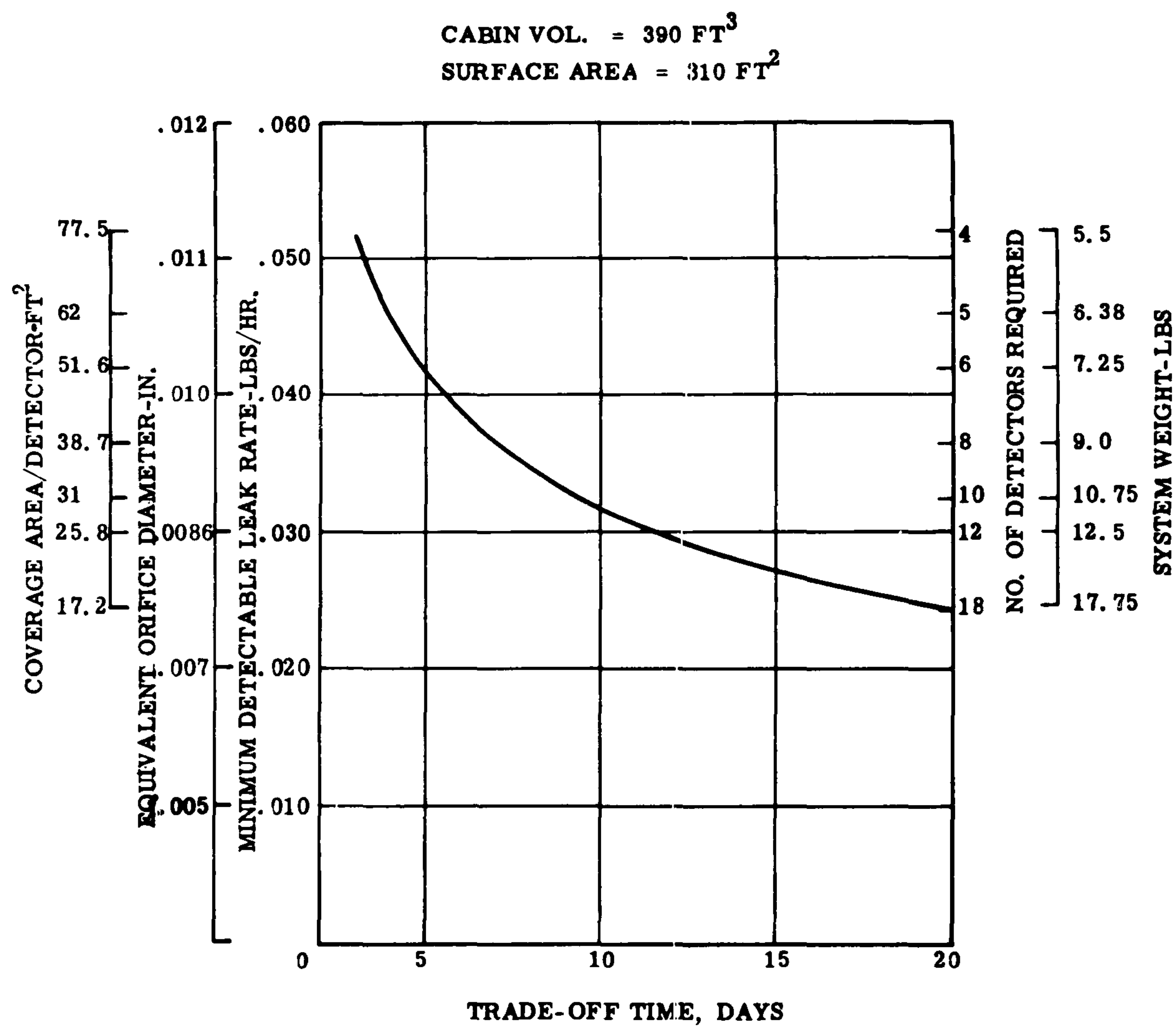


Figure 53. System Trade-offs, Vehicle #1

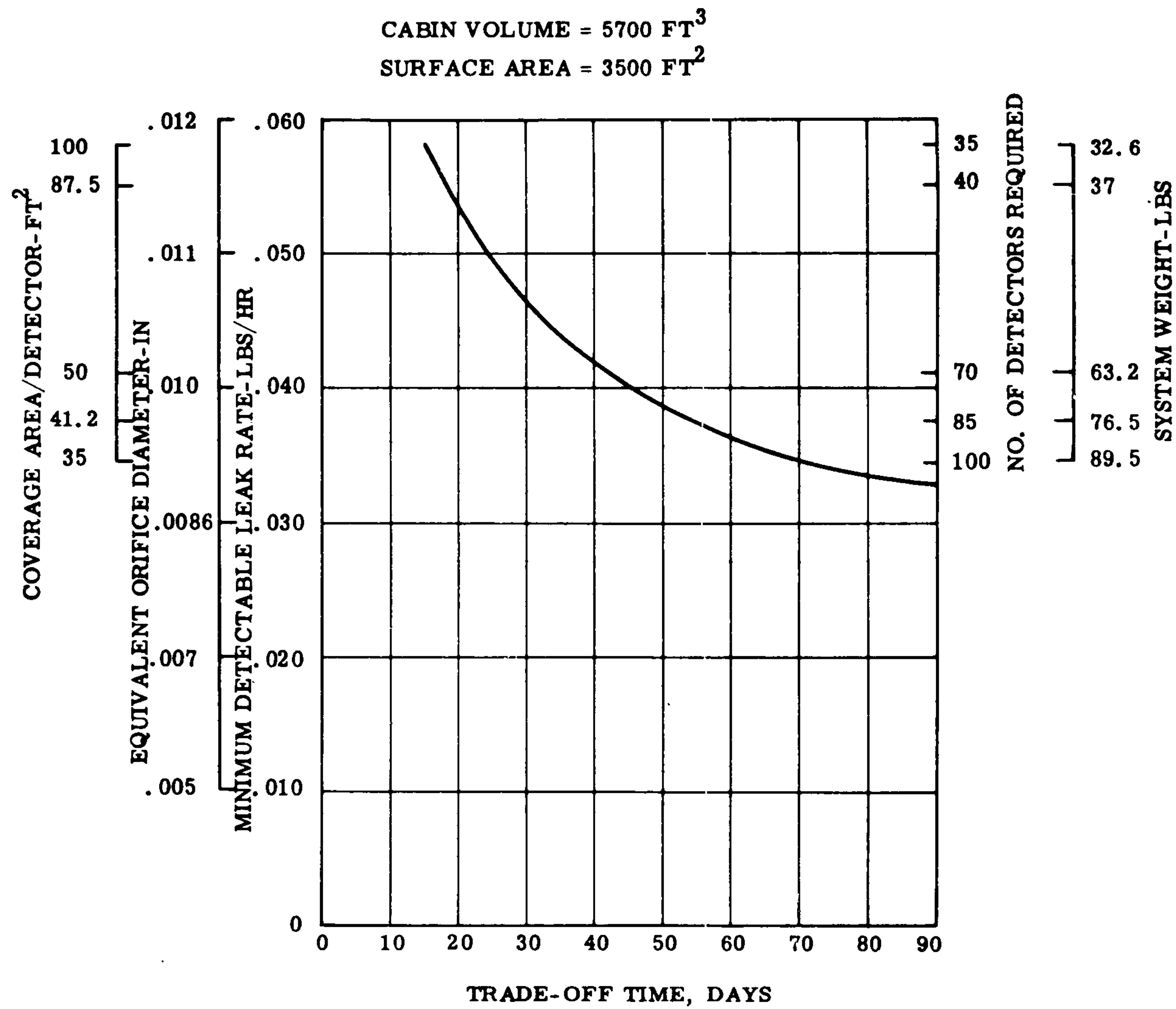


Figure 54. System Trade-offs, Vehicle #2

this minimum detectable leak becomes equal to the mission duration. For smaller leaks, therefore, it would cost more in weight penalty to detect the leak than if the air were allowed to escape, and for larger leaks, use of this system would save weight.

For vehicle #1, then, this leak detection system would operate at the following conditions:

1. Minimum Detectable Leak - 0.0275 lbs/hr

2. No. of Detectors - 14

3. Coverage Area/Detector - 22.2 ft^2

4. System weight - 14.25 lbs.

5. Equivalent orifice dia. for min. leak - 0.0082 inches

Similarly, for vehicle #2, it would not be advantageous to detect leaks less than 0.0365 lbs/hr because it would then take more than 60 days, the mission duration, to obtain a weight advantage with this system. The operating conditions then would be:

1. Minimum detectable leak - 0 .365 lbs/hr

2. Number of detectors - 88

3. Coverage area/detector - 40 ft^2

4. System weight - 79 lbs.

5. Equivalent orifice diameter leak - 0.0098 inch

It should be noted that the system weight could be decreased, for the same minimum detectable leak, by using or developing a detector with a sensitivity greater than 1×10^{-5} mm Hg assumed in the values above. Commercial cold cathode ionization gauges, for vacuum work, have a sensitivity of about 1×10^{-7} mm Hg, and in one instance has a sensitivity of 1×10^{-13} mm Hg. However, design for a lesser sensitivity of 10^{-5} mm Hg has the following advantages:

1. Less attention has to be given to the deterioration of the active cold cathode emitter due to oxidation, sputtering, etc. giving the gauge a greater lifetime and higher reliability.

2. Lower voltages and/or smaller magnets can be used in the design of the detector.

3. Use of a conservative value in the study given above insures the basic feasibility of the system, for, if in development it is found a greater sensitivity is needed for a particular system, it can be achieved readily.

Another fact should be noted. Decreasing system weight by increasing detector sensitivity results in a wider spacing between detectors and a larger coverage area between detectors. This would make locating the small leaks more difficult as the crew would have to examine a larger area. The system, as designed above, would require the locating of a 0.008 inch diameter hole, or its equivalent, in a 4 ft. 8 1/2 in. square area for vehicle #1 and locating a 0.010 inch hole, or its equivalent, in a 6 ft 4 inch square area for vehicle #2. An increase in these values could lead to an impracticability in pinpointing the leak due to the mass of equipment that would have to be moved, and the time consumed in location.

Summary of Ion Gauge Leak Detection

1. Minimum Detectable Leak

   0.0275 lbs/hr for vehicle #1; 0.0365 lbs/hr for vehicle #2.

2. Weight, Volume and Power Requirements

   14.25 lbs, 300 in^3, 2 watts (no leak) - 8 watts (leak) for vehicle #1; 79 lbs, 1900 in^3, 12.3 watts (no leak) - 18.3 watts (leak) for vehicle #2.

3. Time for Detection and Location

   Time for detection almost instantaneous. Location would be given at same time within 22 ft^2 for vehicle #1 and 40 ft^2 for vehicle #2.

4. Complexity and Reliability

   Complexity of the system is reasonable. Reliability estimate would be 0.987/1000 hours of operation/detector.

Comparing the three different methods of leak detection, it can be seen that the ion gauge system is the optimum one. The acoustic detection method, while appearing to be of low weight penalty plus yielding some location information, cannot be established as feasible at this time. The low sensitivity of the pN_2 utilization system and the location problems inherent in this system create a much larger weight penalty than for the ion gauge system. However, portions of this system, or an analogous system can be used to distinguish between the large leaks necessitating cabin decompression and the small leaks where the cabin remains pressurized.

5.3 LEAK LOCATION

As previously discussed, with an ion gauge leak detector system, the general location of a leak would be known within an area of about 4 1/2 feet square to 6 1/2 feet square, depending on the vehicle weight trade-off. The task then remains of pinpointing the leak within this area. The quickest and easiest method of location would be a visual inspection of the wall surface with the unaided eye. It is postulated that this simple type of inspection would locate all leaks caused by penetrations of foreign objects, be they meteoroids or other, through the wall. This is because the wall, being a ductile material will exhibit considerable yielding before fracture, or penetration, will occur. Even during high impact loading considerable dimpling of the wall material would be evident prior to actual penetration. This has been borne out in hypervelocity tests (see Figure 13). Yielding associated with other types of penetration would also cause a localized bulging or dimpling of the wall surface. Since the area of search is reasonable, and since even the smallest leak due to hull penetration would be surrounded by local yielded metal, these leaks could be precisely located with the eye. Therefore, location of leaks caused by punctures of the spacecraft hull by foreign objects will not be a problem.

There are two other types of leaks that could occur, however, that would be difficult to locate visually. One would be fatigue cracks through the hull, and the other, leakage emanating from a faulty seal. In the first case, fatigue cracks would occur under loading that is cyclical in nature, producing alternating stresses in the wall. (Cracks due to impacts would exhibit localized yielding and thus be relatively easy to spot, as mentioned above.) It is extremely doubtful that fatigue cracks would occur as a result of the stresses produced by pressurization of the capsule as a great many depressurizations and repressurizations would have to occur. Other cyclical loading would occur only from the vibrations during propulsion system operation (i.e., during launch, boost and in-flight maneuvers) or from vibrations of rotating or reciprocating equipment that is mounted to the pressure vessel wall. The spacecraft design will, of course, be qualified to meet these vibrational loads so that, for a fatigue crack to occur, two possibilities exist: One failure of the propulsion system, or failure of the rotating equipment so that greater than design loads occur; or, two, a flaw in the cabin wall or welds exists that was missed in the inspection procedures during manufacture. Fatigue cracks, in either of these two conditions, might occur but the probability will be very low. It should be remembered also that extreme vibrational loads can cause failures, other than fatigue, of the cabin wall, particularly at attachment points and in the cabin seals.

The other type of leak that would be difficult to locate visually would be that occurring through a failed seal. Extreme loads, such as

those mentioned above, or loads which could be produced by acceleration, shock, internal explosion, etc., would have a greater effect on seal integrity than on the integrity of the pressure vessel material itself. That is, vibration loads would more likely affect a seal than cause a fatigue crack. Similarly, other loads would affect seals more easily than tearing asunder the cabin itself at any point. In addition, the effect of vacuum could degrade the seal through evaporation and sublimation of the elastomer to the point where leakage occurs. Thus, this type of leakage will be relatively important. Also, if the cabin wall were torn or fractured by these loads, there would be a ductile failure which would be relatively easy to observe.

Therefore, upon indication of a leak, the crew would inspect the cabin wall area in question. If no punctures or fractures of the hull were visible, the next likely candidate for leakage would be the seals. Since there might be many seals in this area, it would be desirable to locate the leaking seal. If the leakage were of a relatively large order of magnitude, it would be possible to locate the leak acoustically. It is possible for the human ear to hear leakage on the order of 0.8 lbs/hour from a 7.0 psia cabin (equivalent to a 0.046 inch dia. orifice). With a Delcon UltrasonicTranslator, this sensitivity is increased to about 0.5 lbs/hour (0.035 inch orifice equivalent). The actual sensitivity would depend on the shape of the leakage area, wall thickness through which the leakage is flowing, and other factors such as surface roughness, etc., which are not defined at this time, so that a greater sensitivity is possible. Higher sensitivity for vacuum leaks might also be possible through design changes in the unit. However the order of magnitude of leakage that can be located by acoustic means is greater than the minimum detection capability, so that, while this could be used to locate some leaky seals, it could not locate all cases of seal failures.

A phenomenon noticed in laboratory tests, might be applicable in this case. That is, when water is brushed over tiny orifices, subject to vacuum on one side, 1 atm pressure on the other, faint hissing noises can be heard as the wet brush passes back and forth over the orifice. Apparently, the liquid interrupts the air flow in such a way as to cause noticeable sound. The size orifices that can be detected this way range down to 0.006 inch diameter (at 1 atm Δp) which is equivalent to a mass flow of about 0.0285 lbs/hr. (0.0087 inch dia. @ 7.0 psia Δp). As seen, this is close to the minimum detectable leak rate (i.e., no further sensitivity is required). However, detecting seal leakage would be somewhat different than detecting orifices. First, the leak in the seal will not be an orifice, but would consist of eroded surfaces or simply a break in the line of sealing contact. Second, the air would probably take several paths past the seal surface flange to reach the failed portion of the seal, and third, the leak would be "buried" beneath flanges or potting. All of these things upset the parameters of this location method, but it still might work for locating seal leakage in some cases.

Another possible method of leak location, unique with the use of cold cathode ionization gauge detectors, takes advantage of the following phenomena. The response of the detector, in terms of microamperes of current conducted, depends on the type of gas present (Ref. 12). For example, typical microampere values for this type of gauge at 1×10^{-4} mm Hg absolute pressure would be 350 μ a for air, 500 μ a for water vapor, 90 μ a for helium. (Exact values may change but proportions should be roughly the same.) Thus if a small jet of helium were played around the seal, and the response of the detector was monitored, a drop in current from the detector would indicate which seal was leaking. Water vapor could also be used, and could tie in with the location method noted in the previous paragraph thus giving two chances to locate the leak with one mode of operation.

Other liquids may also be applicable. These would be brushed over the suspected seal, and, if a leak is present, would flow through the leak, volatize, and thus change the detector current output. For example, acetone is used to leak-check high vacuum systems. The liquid is brushed on over the seals and joints of the system, and leakage is discovered by observing a change in the current of an ion gauge in the system. Acetone is, however, volatile and toxic, and thus would not be suitable for use in a closed environment. Presumably, non-toxic liquids could be found that would produce the desired current change in the detector.

There are several advantages to the use of helium: One, use of helium would result in the greatest known change in current through the detector, thus making detection more sensitive than if water vapor were used. Two, helium has a greater ability to diffuse through leaks, thus the time between release of the gas around the seal and detector indication would be short. Also, small amounts of helium remaining in the cabin atmosphere after use of this method would not have any detrimental effects on men or equipment.

An alternate solution to the problem of pinpointing the faulty seal would be to make repairs, by application of sealing compound, to all the seals in the area. In comparing the above methods of location, comparison should be made to this latter solution, by weight and time required. Time is not important from the standpoint of gas volume lost, because the leakage involved is small, but it is important in the sense that the time required for location of the leak is time that the crew could be assigning to the primary mission. In addition a lengthy time spent in locating a leak would cause some annoyance or frustration to the crew which it would be desirable to avoid.

As a starting point, it is necessary to assume the amount of material and time required to seal an average seal. This will be

assumed as a 1/2 inch bead of sealant laid on a circle 6 inches in diameter. The volume of sealant required is:

$$V = 1/2 \frac{\pi}{A} (.5)^2 \pi (6) = 1.85 \text{ in}^3$$

Assuming the specific gravity of the sealant to be 1.5, the weight of the sealant is:

$$WT. = \frac{(1.5)(62.5)}{(1728)} (1.85) = 0.1 \text{ lbs/seal}$$

The time required to apply the sealant is estimated at 5 minutes. For the acoustic method of locating leaks it will be assumed that half of the faulty seals inspected can be detected by using a combination of a Delcon Ultrasonic Translator and the water brush treatment.

The weight of the Delcon unit is 7 lbs.

The weight of repair, when unit cannot locate leak = 0.05 lbs/seal. Time for inspection is estimated at 3 minutes/seal, plus an additional factor of 2 1/2 minutes per seal for leaks that cannot be located with this method, resulting in a total of 5 1/2 minutes/seal.

Thus, comparing the two systems, the weight increase in repairing all seals is 0.05 lbs/seal. At this rate, 140 seals could be required before the weight penalty equals the weight of the ultrasonic location unit. Since this is a larger number of seals than can be reasonably expected for vehicles #1 and #2 combined, use of an ultrasonic location method would not pay, weightwise. Since the time for location is about the same, for both systems, the conclusion that the ultrasonic method would not be profitable would be unchanged.

In the helium location method (see Figure 55) the gas would be stored in a small pressure bottle fitted with a regulator and small line so that the gas could be directed over the seal-cabin interface. A reasonable discharge rate would be 0.3 lbs./hour. (This is roughly equivalent to the amount of helium that would leak out of the largest size orifice that could not be heard with the human ear.) This is equivalent to about 450 cc/sec. of helium at 7 psia. The helium storage tank would have a weight penalty of about 13 lbs He plus tank/lb He. For a one-hour supply, then, the weight of tank plus He would be:

$$(0.3)(13) = 3.9 \text{ lbs} + 0.2 \text{ lbs for regulator and line}$$

$$= 4.1 \text{ lbs}$$

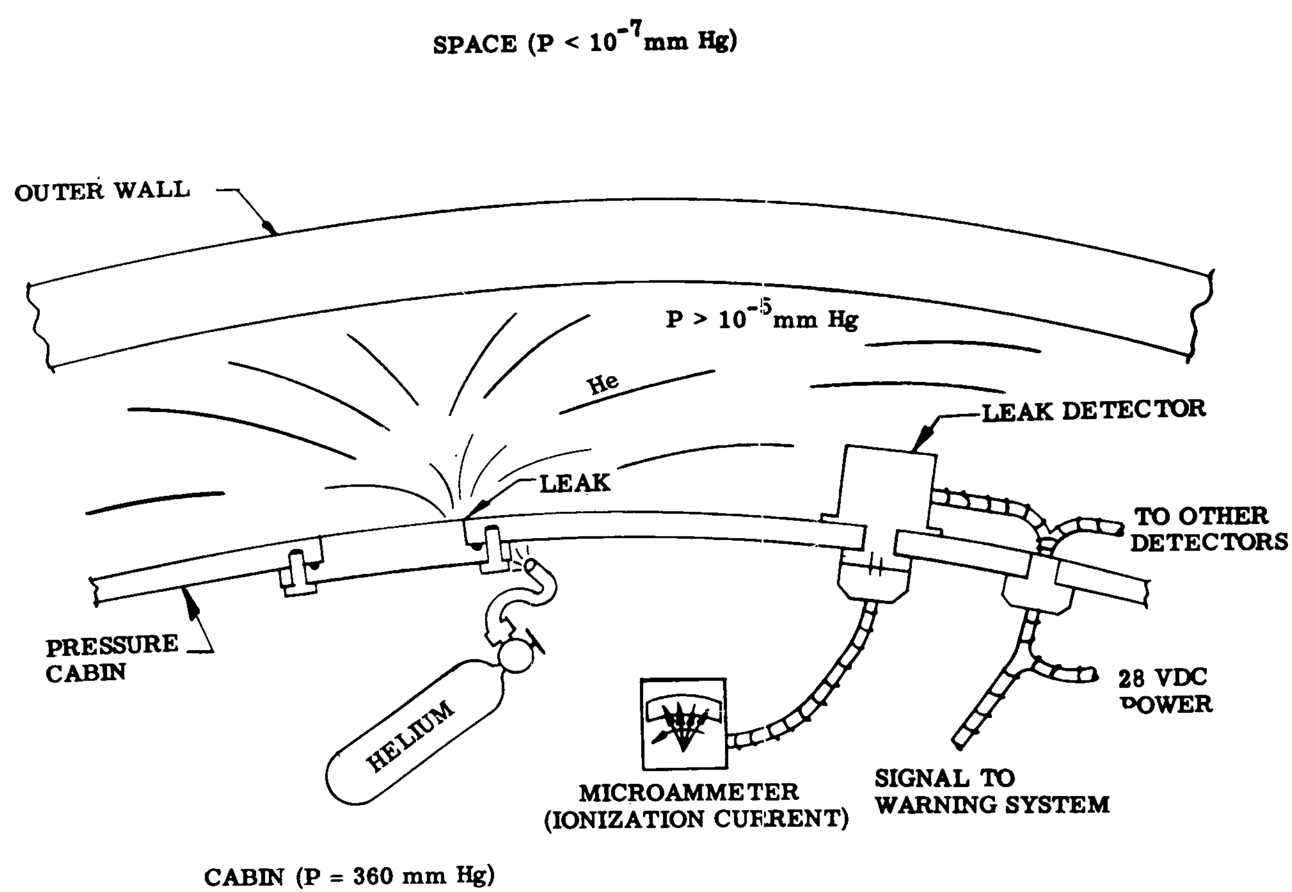


Figure 55. Leak Location - Helium Method

and the volume would be about (for 3000 psi storage)

$$V = \frac{0.3\ (15)\ (1728)}{(0.01035)\ (3000)} \quad = \quad 250\ in^3$$

It is estimated that it would require about 15 seconds to check the average seal with this method. Weight per seal would then be:

$$\frac{4.1}{240} = 0.017\ lbs/seal$$

As seen, this method is both lighter and faster than trying to reseal each leak until the leak is stopped. Thus, this method is the logical choice for the system to use to locate leaks through seals.

As mentioned previously, liquids, for example, acetone, or even water, can be used in this type of location technique. This would most likely result in a lower weight system, but require more time per seal for inspection. The feasibility and desirability of this can easily be established during the development of the leak detection and location system. However, for the purposes of this study, helium, because of its known superiority in diffusing through leaks, known effects on the detector gauge, plus the absence of toxicity, will be chosen as the medium in this location method. That is, helium will be chosen now but subsequent tests in a hardware development program may prove other liquids to be equally or more desirable.

Of some concern, perhaps, would be the amount of the He buildup in the cabin atmosphere through use of this system. This can be calculated, on the basis that all He dispensed remains in the cabin as follows:

$$\rho\ He = 0.01035\ lbs/ft^3 \text{ at } 760\ mm\ Hg$$

$$\rho\ He = 0.0000136\ lbs/ft^3 \text{ at } 1\ mm\ Hg$$

for a 390 ft^3 cabin, for a ρHe of 1 mm Hg,

$$He = (0.0000136)\ (390) = 0.0053\ lbs\ He$$

for each seal inspected, $M\ He = \frac{1}{240} \times 0.3 = 0.00125$ lbs

and $\Delta p\ He = \frac{0.00125}{0.0053} = 0.236$ mm Hg

Thus each seal inspection could raise the pHe in a 390 ft^3 cabin by 0.236 mm Hg. For 100 seals, this would amount to 23.6 mm Hg, a value which would not produce any detrimental physiological effects on men or equipment. The amount of helium in the cabin at any one time would slowly diminish due to normal cabin leakage.

Similarly, for a 5900 ft^3 cabin, each seal inspection would raise the Δ pHe by 0.016 mm Hg; 1.6 mm Hg for 100 seals.

If visual inspection of the seals does not detect the leak, the leak must be caused by a crack indiscernable to the eye. As mentioned previously, the likelihood of occurrence of such a fault is vanishingly small. If one did occur, however, the most likely place to start looking would be along the weld beads. This is a point of stress concentration, and also a point where small inclusions or defects, missed in manufacturing inspection might occur. Any other points of stress concentration, such as cut outs, holes, etc. in the wall would be sealed and thus covered during the seal inspection. To locate such a leak, the helium gas would be directed over all the weld beads, and detector response noted until the crack was found. An analysis, exactly similar to that used for seal detection, would show that this would be a lighter and quicker method of locating these cracks than attempting to apply sealant over all of the welds.

Since the likelihood of these cracks occurring is small, there would be no need to utilize other inspection techniques, such as dye, penetrant, magneflux, etc., since the helium method is required for seals as well. If fatigue failure of the pressure cabin ever becomes a serious likelihood, these methods may find some application.

5.4 REPAIR METHODS

5.4.1 Putty Sealant

A putty sealant such as "Duxseal" or "Albaseal" will effectively seal holes up to 1/4 inch in diameter. It has the advantage of being moldable over ragged, bent edges so that this would not be a problem. The putty sealants mentioned, however, do not harden or cure (i.e., they remain soft and pliable). Adhesion to aluminum, while good, is not outstanding which means that a seal with this material would not be as permanent as may be desired. If left alone the putty sealants would no doubt last a considerable time, but they could be rather easily dislodged and the seal broken if accidently bumped or scraped. To effect a more permanent repair, the putty should cure into a tough material that would also exhibit excellent adhesion to the wall. Ideally, the putty should be a one package material (i.e., it should require no premixing of hardening agents before use). One part sealants that cure into a tough, elastomeric mass usually cure by solvent release, however, and use solvents which are toxic and would be dangerous in a closed air system. A sealant should be developed that utilizes innocuous solvents or uses a constituent in the air as a chemical hardening agent.

Two-part systems could be used, but they would increase the time to effect a repair. The putty sealant could be packaged in small,

individual plastic bags within which a small vial of the catalyst or hardening (curing) agent would be contained. When ready to use, the vial would be broken open by hand (without breaking the plastic putty container) and mixed in with the sealant by working the plastic bag with the fingers. When thoroughly mixed the bag would be broken open and the sealant applied to the leak. A mechanical combination mixer and caulking gun could be devised to mix and apply the sealant.

To eliminate excessive leakage loss while the preparation of the permanent sealant is going on, the puncture could be plugged temporarily with the non-curing putty such as "Duxseal" or "Albaseal." Then when ready, the temporary putty could be removed and the permanent putty applied, or the chemically curing putty could be placed over the previously applied temporary putty. This would form a tough, elastic coat over the soft putty which would have excellent adhesion to the wall and give a much higher degree of permanency to the seal.

This latter method was tried in the laboratory by applying RTV-102 silicone rubber sealant over Duxseal. RTV-102 is a one-package compound. When first applied it is a thixotropic paste which later cures to form a silicone rubber seal. It has fair adhesion to metals. It would not be useful in a space cabin as it releases acetic acid upon curing which is toxic, but it serves to illustrate the repair method involved. The seal formed by this combination is permanent. The silicone rubber forms a tough outer covering for the Duxseal and, by adhering to the metal, makes it much more difficult to dislodge. A sealant with greater adhesion than the RTV-102 would not be difficult to develop, and this would raise the degree of permanency and confidence. Incidentally, the RTV-102 alone would not be satisfactory for sealing any but the smallest punctures and cracks because when first spread, it is too thin and extrudes easily. A curable putty that could be used alone to seal holes up to 1/4 inch diameter should have a consistency of about 65-100 (as measured by ASTM D5-52 with 100 gram load) when applied in order to prevent extrusion through the puncture.

Cracks may also be sealed by methods similar to those used for punctures. Permanency is required so that the sealant must cure into a tough coat which adheres well to the wall. Again, a one-part or two-part sealant could be developed, except that the consistency does not have to be as high as was necessary in sealing punctures since extrusion will not be as great a problem. If a two-part sealant system is used, the leakage can be temporarily stopped with the pliable putty until the permanent sealant is prepared. The types of repair for cracks mentioned above would have little, if any, structural value. If structural repair (i.e., repair of the load-carrying capability of the structure) is required, another method must be used.

The putty sealant can also be used to repair leakage through the seals in the space cabin. In this case, the putty would be smeared over the line of contact between the seal surface flange and the cabin wall, thus completely sealing it. The same remarks about permanency of repair stated above apply in this case also. This method of repair would be applicable to the fixed seals but could not be applied to any rotating seals or seals that are periodically broken, such as hatch or air lock seals. The repair would cure to form a tough, highly adhesive seal that could not easily be broken or jarred loose.

5.4.2 Liquid Sealants

Liquid sealants that could be applied with a brush, roller or spray can could be used to repair cracks, very small punctures and leaking seals. The sealant, after application, should cure to a tack-free state and exhibit good adhesion to the metal surfaces. Again, a one-part compound is desired. However, since the order of magnitude of leakage is small in this case, the time required to mix a two part compound could be tolerated.

Two-liquid sealants demonstrated their ability to seal cracks and pinhole leaks in a laboratory test. One was Duro plastic rubber; the other, Duro plastic aluminum, both thinned with toluol to a watery consistency. These were brushed on over cracks and 0.006 inch diameter holes in thin aluminum plates subjected to vacuum on one side, and 1 atmosphere pressure on the other. Both sealed the leaks immediately and dried to a permanent film. Since the solvents used in these compounds are toxic, they would not have direct applicability to leak repairs in a closed environment, but the repair method was demonstrated to be feasible.

One other type of sealant that could be "flowed" over cracks and seals would be one of the Apiezon waxes. These are low vapor pressure waxes that have found use in sealing vacuum systems. The wax, when heated, becomes a liquid that can be flowed into recesses around seals or lap joints or over cracks. When cooled the wax hardens but could remain soft or hard, depending on the type used. Apiezon "hard wax W" was used in tests to seal both cracks and punctures up to 1/4 inch diameter successfully. As such, it has some of the attributes of both the putty-type sealant and the liquid sealants. Adhesion is good and at this time no toxic outgassing is known to exist.

The disadvantage of the use of Apiezon wax is that it has to be heated before being applied. This could best be accomplished by designing a special "gun" with a hollow copper tip that could be heated electrically. The wax would be forced through this hot tip, melted and flowed over the crack or seal. Interchangeable tips could be used depending on whether a large plug of wax was needed (for a puncture), or a thin ribbon (for cracks), or a bead (for seals).

The gun would have to be small and compact to reach tight corners with limited accessibility.

In comparing a liquid sealant with a putty sealant for the repair of cracks and seals, the results are about equal. It would require less time to repair a seal with a liquid sealant than with a putty sealant, since it would be easier to cover large areas quickly with a brush or spray than by molding putty in place with the fingers or a spatula. For small seals this time difference would be insignificant, but in sealing large areas it could amount to 5 or 10 minutes. For the same large area, say a 30 inch diameter hatch, the weight of putty sealant required would be about 0.5 pound. Liquid sealant applied in a film 0.010 inch thick, 1 inch wide would weigh about 0.05 pounds, or 1/10 as much. Thus the liquid sealant is superior on a weight and time basis; however, since such repairs would be required only in rare emergencies, the absolute magnitude of the time and weight advantage would be small.

One advantage of a liquid sealant would be in the sealing of emergency hatches which must open quickly. A putty sealant, because it cures into a tough, strong seal with excellent adhesion, would impair the functioning of such a hatch, while the thin film of a liquid sealant would break easily when necessary. Apiezon wax would also be suitable for this purpose. The wax, at least the hard wax W, shears fairly easily and thus would not impair the action of the hatch. With respect to weight and time required for repair, Apiezon would lie between the putty sealant and the liquid sealant.

5.4.3 Patches and Plugs

There are many different types of patches that can be applied to seal a puncture. For permanency and reliability of repair, all patches require an adhesive sealant, either integral with the patch or applied separately, to bond the patch securely to the wall. The alternative to this is to use self-tapping screws or blind fasteners to hold the patch, or weld or braze it into place. In both cases at least part of the patch would have to be metal.

It becomes obvious upon observation of a few hypervelocity impacts or other punctures of a ductile material such as aluminum, that a patch cannot be installed flush with the wall unless the damaged area is reworked. Thus, the patch has to be flexible enough to mold over the bent up edges, be permanently "hollowed out" or depressed so that it fits over the puncture, or the puncture damage cleaned up. If the puncture is in an area free of obstructions, there are a number of patches that could be used for sealing the hole which do not require rework of the damaged area. However, this is only true in this one specific case. The puncture might also be located adjacent to a structural member (i.e., beam, stringer, longerons, angle, connector, bracket, etc.), which would make installation of a "standard" patch impossible as shown in Figure 56. Thus, for

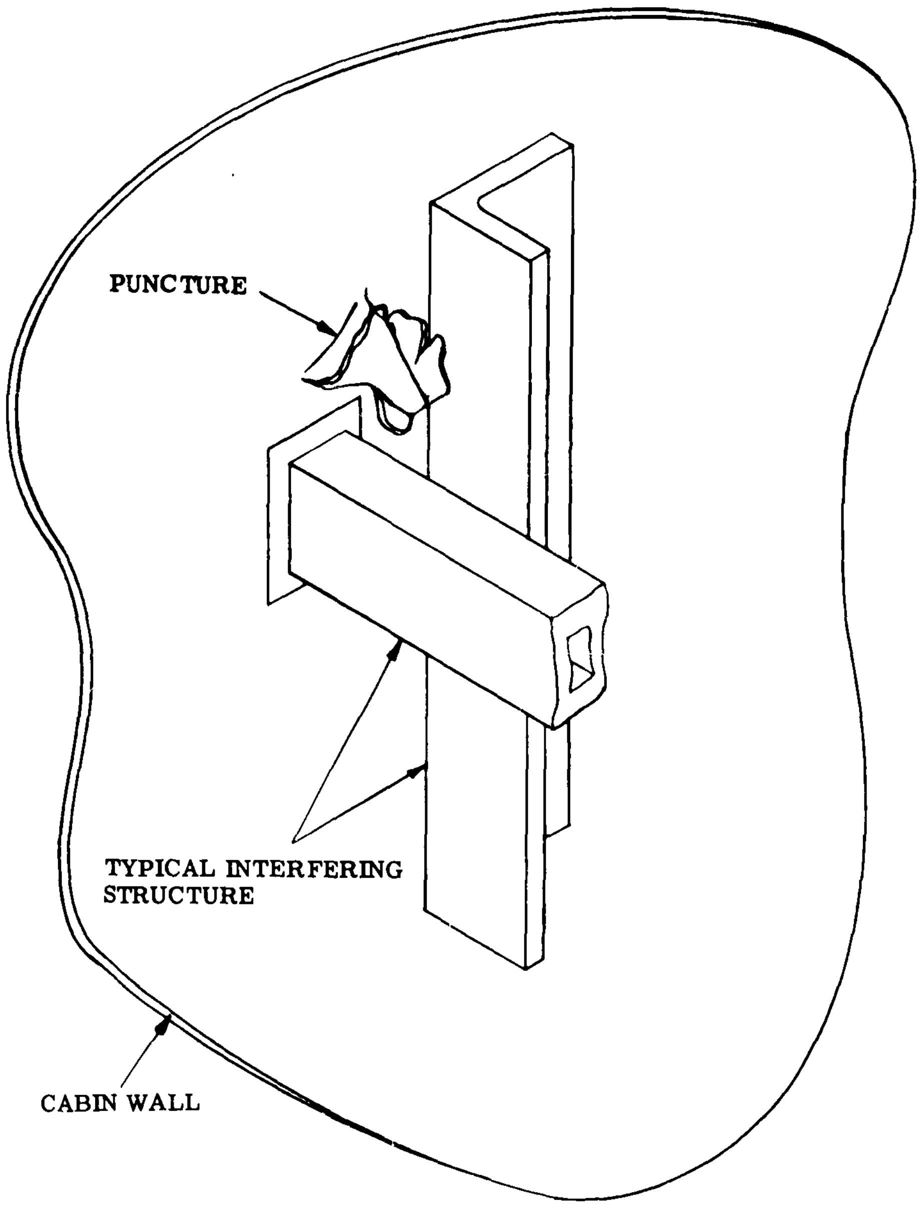


Figure 56. Puncture with Limited Accessibility for Repair

punctures where a putty adhesive sealant can be used without extruding, it is preferred over a patch because of its greater versatility in sealing punctures in many different locations.

In the case of plugs, the same would hold true. That is, for a plug to be effective the hole should be drilled out clean so that it is nearly round. Under these circumstances, an elastomeric plug would seal effectively, as witnessed in a laboratory test. However, it is doubtful if this repair could be made with the cabin pressurized as is desirable for the smaller punctures, because of the length of time required and the large hole resulting from the clean up operation. The repair must include any cracks extending radially from the hole; thus, the final hole would be large. The foregoing discussion clearly indicates that a putty sealant is preferred for the smaller punctures.

For large ruptures of the pressure cabin, when decompression of the cabin occurs, time can be taken to remove any bent, protruding edges. In a long duration satellite, such as a space station, motor driven tools should be available to accomplish this rework. If they are not, the rework could be done with a few simple tools, such as a nibbler, pliers, hammer and chisel. With motorized tools, the damaged area could be quickly and easily reduced to a clean hole. The advantages of doing this are 1) It enables a relatively simple patch or plug, that is adaptable for various size punctures, to be used for the leak repair; and, 2) it eliminates possible interference between the repair and the equipment mounted close to the wall.

If the puncture should occur in an area free of surrounding obstructions, there are a number of methods for repair that could be employed, once the damage is cleaned up. One method is to bond an elastomeric patch over the hole. This patch should be fairly stiff, as it requires sufficient strength to resist the force of the cabin pressure, and it must be impervious. The bonding agent should be strong, so that the seal will be permanent and act as a sealant between the patch and the wall. Since the patch must be stiff, it would also be springy, and would therefore have to be held against the wall until the adhesive had set. For this reason the bonding agent would have to set quickly. It is possible that the putty sealant developed for the smaller punctures could double as the bonding agent in this case, if the strength is high enough and the cure fast. If not, however, a fast curing epoxy adhesive or a contact cement should be suitable.

It would, of course, be possible to bond a metal plate, instead of an elastomeric patch, to the wall. Because of wall contour, however, it would be more difficult to obtain close contact with the wall at all points using a metal plate than it would be using an elastomeric patch. The relative difficulty of the metal plate would depend on size and thickness of the plate, wall contour, allowable spacing, etc., and it might be suitable in a few instances, but would not be as adaptable as the elastomeric patch. A better means of affixing the plate would be to install it with blind mechanical fasteners similar to Rivnuts. The fasteners would be o-ring sealed to prevent leakage and, before installing, the one side of the plate would be smeared

with the putty sealant to effect a tight seal. This repair would have good permanency, some structural (i. e., load carrying) ability, but would require a relatively long time for installation.

Another type of repair having a high degree of permanency plus some structural ability would be a self-brazing plug. This would operate on the same principle developed for Deutsch Pyrobraze Fittings. A ring of brazing material would be located underneath the lip of the plug. On top of the plug would be a chemical fuel (known as "Exotherm" in the Deutsch fittings) imbedded in insulation. Upon touching the two electrical leads to a battery (1. 5V), the fuel would ignite, producing the heat required to braze the plug permanently to the wall. The insulation could then be removed leaving a neat, permanent repair as shown in Figure 35. If the wall is reasonably flat, the plug can be held in place with anything handy (screw driver, ruler, etc.) for the few seconds required for brazing. Uneven wall contour could interfere with this procedure, however. The plug would therefore have to be designed with self-locking features to draw the wall flush with the plug, or a tool designed to flatten the wall locally before installing the plug.

If the repair is to be made in a tight corner with surrounding obstructions, it would not be practical to use the above methods. That is, it would not be practical to carry in the spacecraft specially designed plugs and patches to fit every situation that could occur. Therefore, repair in these difficult areas strongly suggest a patch that can be cut to fit the puncture as required. Since the wall would not support the patch on all sides, the patch would be applied and the putty sealant added to seal any chinks or cracks not sealed by the patch. A metal patch would be required to eliminate flexure due to cabin pressure. This would be necessary to eliminate excessive stress on the putty sealant which seals at least one side of the patch with the cabin. Figure 57 illustrates this type of repair.

5.4.4 Self-Sealing Methods

A self-sealing layer bonded to the pressure cabin wall will provide an automatic repair method for the smaller punctures. The advantages of this are self evident. It eliminates the need to detect, locate, and subsequently repair the small punctures. Repair would be almost instantaneous, and very little atmosphere would be lost. However, in the design of any self-sealing layer, there would be a maximum size puncture that could be sustained and sealed. Punctures above this size would create cabin leakage. This leakage could be large or small, depending on the extent to which the sealant material plugs the puncture. If provision is to be made for the repair of these larger punctures, a leak detection and location system of the type determined previously, would be required. In this case, therefore, the real benefit of a self-sealing cabin wall would be the automaticity of repair. That is, for many punctures, the crew would not be required to locate the leak, or repair it.

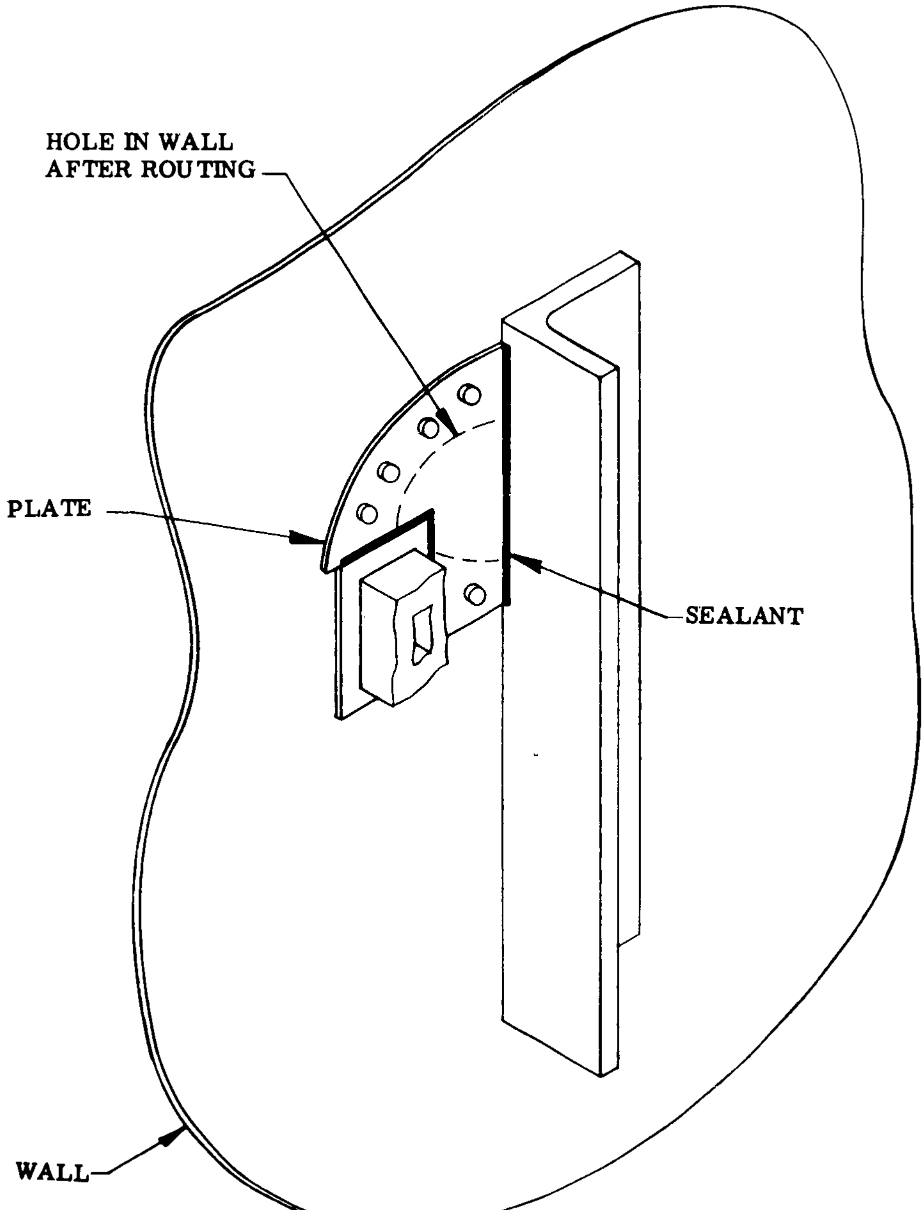


Figure 57. Repair - Limited Accessibility Puncture

It is desirable, of course, to design a self-sealing wall that would seal automatically all punctures, both large and small. This can be approached realistically by providing self-sealing against all punctures within a certain probability of occurrence. The large punctures that could not be sealed in this case would have a low enough probability of occurrence that the risk could be taken. In general, the maximum size puncture that could be sealed with self-sealants is a function of the thickness of the sealant layer. The thicker the sealant, the larger the hole that can be resealed and vice versa. Reference 13 presents a self-sealing design that effectively reseals punctures created by a 1/8 inch diameter round steel pellet, weighing 140 mg, traveling at 7000 ft/sec. As evidenced in this report, special attention had to be given to the selection and design of the confining structure for the sealant and the backup sheet to keep the puncture hole size as small as possible.

Using the above results, an approximation of the probability of sustaining a meteoroid penetration that could not be resealed can be made. First it will be assumed that a meteoroid of 1/8 inch equivalent diameter will create the same size puncture as the 1/8 inch diameter pellet used in the tests. Then, meteoroid punctures smaller than this would be resealed. To be conservative, the puncture size will be based on porous meteoroids and the Hughes maximum mass population curve. (The porous meteoroid has the smallest mass, hence highest probability of impact, for a set equivalent diameter.) Now, a porous meteoroid of 1/8 inch equivalent diameter would have a mass of 10^{-3} grams. The probability of impact with meteoroids of this size or larger would be 10^{-9} impacts/m^2/sec or 8.0×10^{-4} impacts/100 ft^2/day. For vehicle #1, with a surface area of 310 ft^2 and a mission of 14 days, the probability of sustaining an impact with a meteoroid larger than 1/8 inch diameter is 0.035 impacts/mission, or 28.6 missions/impact. This means that, on a probability basis, one out of every 28.6 missions will sustain a meteoroid penetration of sufficient size to cause permanent leakage.

Similarly, for vehicle #2, with 3500 ft^2 surface area, and mission of 60 days, 1.7 meteoroid penetrations will occur in each mission, of sufficient size to create permanent leakage. These probabilities can be further reduced if a meteoroid bumper shield is incorporated into the design of the vehicle. It may, of course, already be present in the form of a re-entry shield, etc. If we assume that this shield breaks the impacting meteoroid into ten separate, equal parts, and that these fragments are spread out so that they can be treated separately when they hit the pressure cabin, the probabilities determined above will be reduced by a factor of 10 (i.e., 0.0035 and 0.17 impacts per mission for the two vehicles, respectively). In addition, a thicker layer of self-sealant material would be able to sustain and repair a larger puncture, and the probabilities above could be reduced in this manner.

It is apparent, therefore, that a self-sealing cabin wall design for the purpose of reducing leakage through meteoroid punctures to an

acceptable minimum is feasible. However, the self-sealant could not eliminate leakage through faulty seals, or large punctures or ruptures caused by collision, explosion or other large structural failure, and hence, these hazards remain.

A self-sealing cabin wall would also impose a relatively large weight penalty on the vehicle. The specific gravity of the self-sealing material would be between 0.95 and 1.5 depending on the particular brand selected. Polysulfide rubber compounds are at the top of the weight scale with a specific gravity of 1.5. Other possible self-sealants are the silicone rubber compounds, specific gravity 1.3 - 1.4, and polyurethanes and polybutenes, specific gravity about 1.2. A lighter weight self-sealant could be compounded from a mixture of Diene and natural rubber (Ref. 14) and would have a specific gravity of about 0.95.

The exact choice of a self-sealant material requires an extensive test program for evaluating the multitude of possibilities. Each of the above compounds can be formulated to give different properties of hardness, tackiness, nerve, elasticity, etc., by adding various resins or varying the cure. The self-sealing properties of each can then be determined. Also of prime importance would be tests for vacuum resistance, and temperature effects. Meteoric impacts would produce short-duration high temperatures which the material must withstand if it is to be successful. In general, however, the self-sealant material should probably exhibit a lack of nerve, and a light cure with the addition of tackifying resins. The latter would help on resealing. Lack of nerve would reduce the size of the puncture in the material (an elastomer having high nerve would tear extensively under impact). It should retain sufficient cohesiveness and nerve, however, to resist extrusion through the puncture. A polysulfide rubber compound (Ref. 15) was tested in the laboratory for self-sealing properties. A 1/2 inch thickness of this material successfully resealed punctures up to 0.135 inch diameter under a pressure differential of 1 atmosphere. This material thus shows possibilities and could most probably be improved although the actual resealing ability should be tested under a dynamic situation, where the penetration would more closely approximate a meteoroid puncture.

For a 1/4 inch thickness of self-sealant material, then, (the same thickness as used in reference 13), the weight would be anywhere from 1.25 lbs/ft^2 to 1.955 lbs/ft^2. The weight of the confining structure will not be added as it is assumed that this weight materially adds to the structural ability of the pressure cabin, and thus should be included in pressure vessel weight. For vehicle #1, the weight penalty for a self-sealing wall construction would be a minimum of 384 lbs. and a maximum of 606 lbs. for a 1/4 inch thickness. For vehicle #2, the weight penalty would be between 4340 lbs. and 6850 lbs. for the same thickness.

As seen, the weight of a leak detection and location system is much less than that for a self-sealing wall. Unless a great many meteoroid punctures are anticipated, and this is unlikely because of other harmful effects (i.e., damage to men and equipment), it would not pay on a weight basis to include self-sealing for the entire cabin. There are some cases, however, where self-sealing construction would be required – for example, for those areas of the pressure cabin that are inaccessible and could not be reached by the crew. Refer again to Figure 57. If a meteoroid, or any other object, penetrated the cabin behind the angle, either partially or totally, air could leak underneath the angle at any point and out through the puncture. In repairing a puncture of this type, the angle would have to be sealed with the putty or liquid sealant along all points of contact with the cabin wall. This could be extremely difficult to accomplish if there were adjoining or overlapping structure in the area. A method of overcoming this would be to either seal all structure attached to the inside of the cabin wall along all edges during manufacture, or incorporate self-sealing panels under this structure. Thus, in the former case, only the part of a puncture extending beyond the edge of the angle need be resealed, and in the latter case, the puncture would seal automatically. Aside from this case, self-sealing structure should be included for all parts of the cabin which cannot be reached by the crew. To keep the overall vehicle weight down, this self-sealing structure should be kept to a minimum. It follows, therefore, that every effort should be made during the initial design to allow accessibility to the cabin wall through removable equipment, floor, etc.

5.4.5 Repair Methods - Summary

In an effort to assess the relative merits of the various proposed techniques of leak repair, laboratory tests were performed. The tests were designed to yield qualitative information on the relative merits of the different repair methods rather than quantitative information. As such, no particular attention was paid to the individual properties of the repair material, such as toxicity, vacuum stability, temperature effects, etc., but rather information was gained concerning permanency of repair, complexity, reliability, time required, and applicability to each different method (i.e., plug, patch, putty, etc.)

In the test set up, the punctures or cracks were simulated in an aluminum plate 0.040 inch thick. The plate was affixed to a small chamber that was evacuated with a vacuum pump. The pump was capable of producing a vacuum of about 5 microns in this chamber if the leak in the plate were sealed tight. Thus, the repair was made to the puncture or crack in the plate and it was easily noted, by means of a pressure gauge in the vacuum chamber, if the seal were effective. The ΔP across the seal was 1 atm.

Punctures were simulated by actually punching a hole in the plate with a center punch or similar tool (see Figure 58). This produced sharp, protruding edges around the hole as would occur in the puncture of a pressure cabin. Cracks were simulated by cracking the plate with a chisel, then flattening the plate with a hammer (see Figure 59). Cracks were, then, relatively flush with the surface of the plate. A summation of the tests and results follow.

Putty Sealants

Figure 60: "Albaseal" and "Duxseal" sealant putty successfully sealed punctures up to 1/4 inch diameter. For i/4 inch diameter and above, extrusion of putty rendered repair inadequate. Permanency was inadequate as both putties could be removed from the plate easily although "Albaseal" showed more adhesion than "Duxseal".

Figure 61: When "Duxseal" was covered with RTV-102 silicone rubber adhesive sealant, repair was much more permanent. RTV-102 cures to form silicone rubber, "Duxseal" and "Albaseal" do not cure but remain pliable.

Figure 62: Apiezon"Hard wax W" sealed cracks and punctures up to 1/4 inch in diameter. In a test on a 1/4 inch diameter puncture, the wax had extruded considerably after 4 hours although the seal was still good. Repair was permanent. For applying, the wax was heated and melted over the cracks and punctures where it cooled and formed a hard plug.

Patches

Figure 63: Polyethylene tape successfully sealed cracks and very small punctures. For larger punctures with protruding lips (approx. 1/8 inch diameter), there was difficulty in obtaining a good seal with the tape. Permanency is high but reliability of obtaining a good seal is low.

Figure 64: A rubber plug, hollowed out at one end successfully sealed punctures. Size was limited only by diameter of hollowed out area (approximately 1 inch diameter). The plug was capped over the puncture with the edges sticking up into the hollowed out area. For permanency and reliable sealing, an adhesive sealant (RTV-102) was used to bond the plug to the plate.

Figure 65: A 1/8 inch thick silicone rubber patch sealed a 1 inch diameter clean hole that was drilled through the plate (i. e., no raised edges). For permanency, the patch was bonded to the plate; however, for sealing only, no bonding agent was needed. This type patch also sealed a 1/2 inch diameter (approx.) puncture with raised edges in one case but in another case the patch was cut by an edge and the seal broken. For a patch of this type to be successful it must combine flexibility for good sealing with toughness to resist puncture from sharp edges.

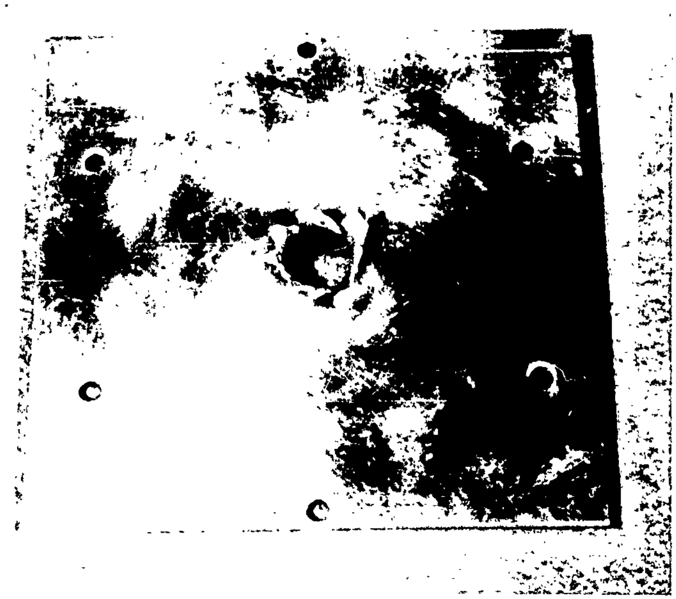


Figure 58. Typical Puncture

Figure 59. Typical Crack

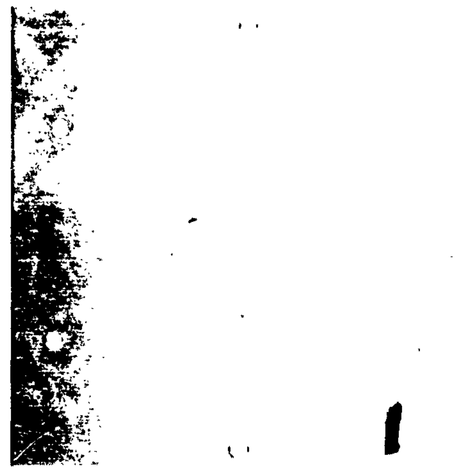


Figure 60. Albaseal Over Puncture

Figure 61. RTV-102 Over Albaseal Over Puncture

Figure 62. Apiezon Over Puncture

Figure 63. Polyethylene Tape Over Small Puncture

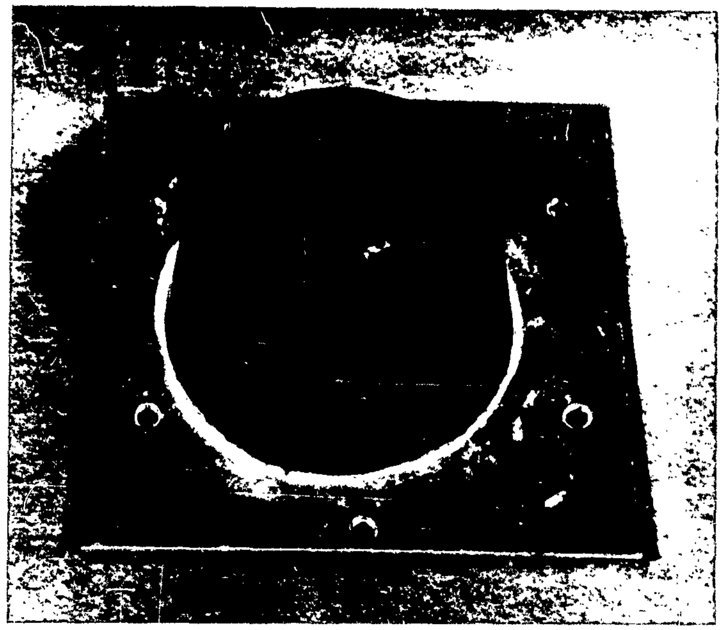


Figure 64. Hollowed-Out Plug Over Puncture

Figure 65. 1/8" t Silicone Rubber Patch Over Puncture

Plugs

Figure 66: A solid rubber plug successfully sealed a 1-inch diameter clean round hole. Seal was easy to break if plug was bumped or moved but it always resealed immediately. Addition of a sealant bond between plug and wall would make this repair more permanent.

Liquid Sealants

Figures 67 & 68: Liquid sealants, represented by "Plastic Rubber" (Figure 67) and "Plastic Aluminum" (Figure 68) thinned with Toluol to a watery brushable consistency, sealed cracks and pinhole punctures. The limit in size puncture sealed was between 0.010 and 0.020 inch diameter. The sealant was applied with a brush.

Self Sealing Materials

Figure 69: A 1/2 inch thick layer of polysulfide rubber self-sealant (Ref. 15) sandwiched between two 0.040 inch aluminum plates successfully resealed punctures of up to 0.135 inch diameter. Punctures of 0.073 inch diameter and 0.091 inch diameter resealed almost immediately. For larger punctures of 0.112 inch diameter and 0.135 inch diameter sealing was progressive and required considerable time (approximately 24 hours) to obtain a tight seal. Leakage up to this point was very small, however, as fair resealing occurred immediately after puncture.

Using these qualitative results, plus the concepts developed in the preceding discussion, a relative trade-off between the many repair methods can be made. This is shown in Table 8 for repair of small punctures and cracks (Part A), repair of large punctures (Part B), and repair of seals (Pact C). As shown, each of the repair methods is evaluated for its ability to meet the requirements of permanency, complexity, reliability, time required, and applicability. Weight, volume, and power required are not shown because the differences between the repair methods, in this case, are negligible. This is because repair of leaks is an emergency requirement, rather than a planned activity, and therefore the number of repairs in any one mission is expected to be small; hence, while differences in weight and volume do occur, their absolute magnitude is but a few pounds. Permanency, reliability, and applicability are rated, high, medium, and low in descending order of merit. Complexity and time required are rated low, medium, and high in descending orders of merit. Rating is determined by simply substituting a number for the best rating obtainable in each column, and subtracting one from this number for any rating below the best. The numbers can then be added horizontally for each repair method and the highest total would be rated No. 1, next highest 2, and so forth.

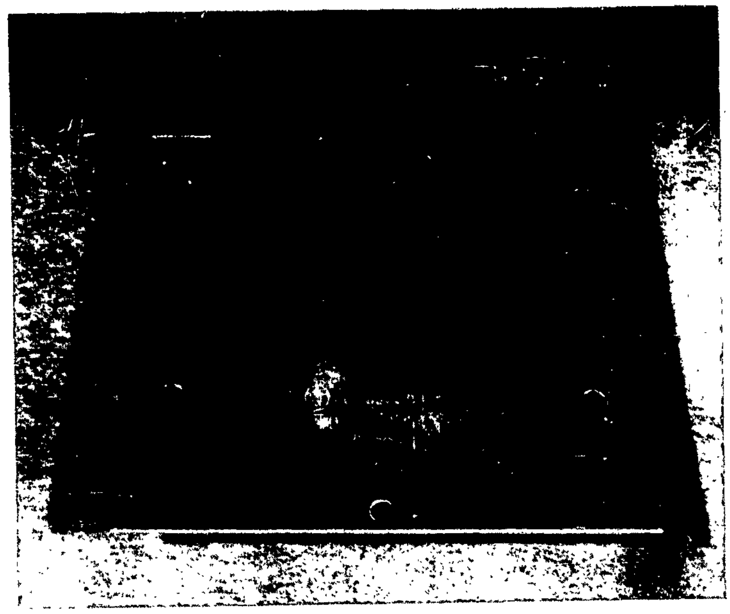


Figure 66. Plug in Round Hole

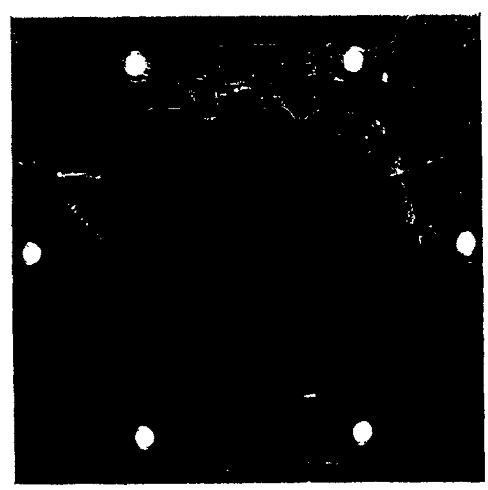


Figure 67. Plastic Rubber Over Crack

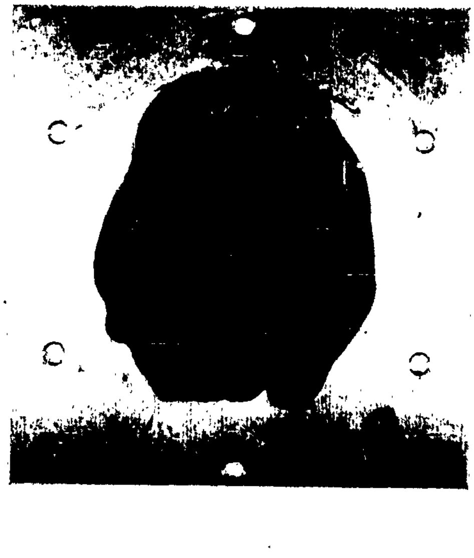


Figure 68. Plastic Aluminum Over Crack

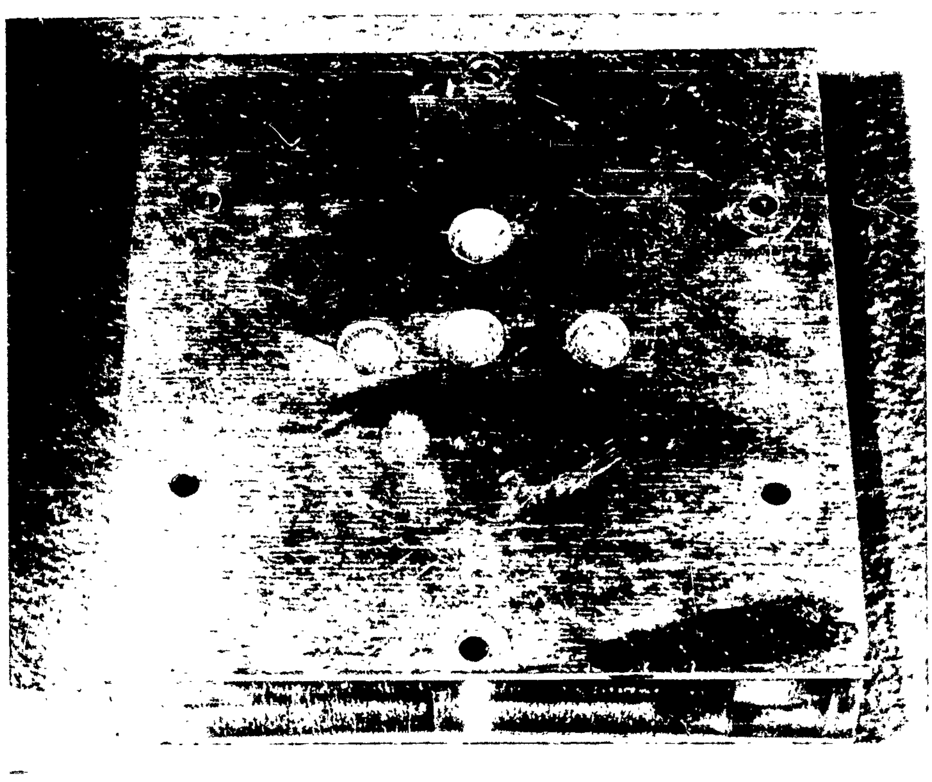


Figure 69. Self-Sealant Sandwich

TABLE 8. TRADE-OFF SUMMATION - REPAIR METHODS

A. Small Punctures and Cracks - Cabin Pressurized, no rework of damaged area.

Requirements

Repair Method	Permanency	Complexity	Reliability	Time Required	Applicability	Rating	Remarks
1. Putty sealant-curable one part compound	high	low	high	low	high	1	Forms tough, durable seal.
2. Putty sealant-curable two part compound	high	medium	high	high	high	3	Same as 1. Epoxy type has unexcelled strength and adhesion.
3. Liquid type - cures to form film	high	medium	medium	low	low	4	Good for only the smallest holes and cracks.
4. Patch, elastomeric, adhesive sealer backed	medium	low	medium	low	low	4	Reliability & applicability low because of interference from protruding edges of puncture.
5. Patch, hollow, adhesive sealer backed	medium	low	high	low	medium	2	Tight corners problem.
6. Patch, metal, depressed center, gasket adhesive sealer	medium	low	medium	medium	medium	4	Tight corners problem.
7. Plug, elastomeric plus sealant	high	low	low	medium	low	5	Jagged punctures problem.
8. Plastic sheet, adhesive backed	medium	low	medium	low	low	4	Good for only smallest punctures and cracks.

TABLE 8. TRADE-OFF SUMMATION - REPAIR METHODS (Cont'd)

B. Repair of Large Punctures - Cabin depressurized - rework allowed.

Repair Method	Requirements					Rating	Remarks
	Permanency	Complexity	Reliability	Time Required	Applicability		
1. Patch, metal, mechanically fastened, sealant backed	high	high	high	high	high	2	Only method applicable to odd size punctures, tight corners, all situations short of structural repair.
2. Patch, metal, bonded	high	medium	low	medium	low	4	Hard to fit contoured wall.
3. Patch, elastomeric, bonded	high	medium	medium	medium	low	3	Same as 2.
4. Plug, elastomeric, or metal bonded and sealed	medium	low	high	low	medium	1	Cannot be used in every case.
5. Plug, metal, self-brazing	high	medium	high	low	medium	1	Same as 4.

TABLE 8. TRADE-OFF SUMMATION - REPAIR METHODS (Cont'd)

C. **Repair of Seals.**

Requirements

Repair Method	Permanency	Complexity	Reliability	Time Required	Applicability	Rating	Remarks
1. **Putty sealant-curable one part compound**	high	low	high	medium	medium	2	Good for all but breakable seals.
2. **Putty sealant-curable two part compound**	high	medium	high	high	medium	3	Same as 1.
3. **Liquid brush, roll or spray-on type-cure to form film**	high	medium	high	low	high	1	Good for breakable seals but must be resealed after broken.

The requirement of permanency includes a judgement of the reliability of maintaining a seal with the repair for the mission duration. Reliability is meant to include the ability of the repair method to form an adequate seal initially. Applicability is the ability to repair all leaks in the particular category, and complexity includes ease of applying the repair material.

Briefly summing up the results of the tables, a curable putty adhesive sealant is the best method of repair for small punctures and cracks up to the size necessitating cabin decompression. Since the maximum size puncture repaired by the method can be quite large (0. 9 inch diameter for vehicle #2), the putty will have to be quite stiff to resist extrusion. If the proper combination of consistency, adhesion, and durability cannot be found in one compound, a non-curing stiff putty can be used to seal the leak initially, and the curable sealant spread over this to form a tough, permanent seal.

For repair of large punctures, both a self-brazing plug and a simple plug with sealant appear as the best choice. Choosing between the two, the self-brazing plug sacrifices more complexity for increased permanency, and this would appear to be the better selection of the two. Neither, however, would be useful if the puncture were in a tight corner. For this case, the first method (i. e., a metal plate mechanically fastened with the chinks and cracks filled in with the putty sealant,) is the only one that will suffice. Thus, where possible, self-brazing plugs will be used, and when required, a metal patch will be installed as a seal.

In repairing seals, a liquid sealant brushed or sprayed on and cured to form a thin sheet or film is optimum. A putty adhesive sealant could be used but might interfere with breakable seals (i. e., seals that may have to be opened at some time).

VI. SYSTEM DESIGN CONCEPTS

6.1 BASIC ASPECTS

There are four basic aspects that require integration into the overall system. They are:

1. Detection of the leak

2. Warning

3. Location of the leak

4. Repair

This section of the report will deal with the design concepts for each as well as synthesis of the system itself.

6.2 LEAK DETECTION SUBSYSTEM

The leak detector itself is a form of a Phillips, or cold cathode, ionization gauge that has found use for many years as a pressure measuring device for high vacuum systems. To gain an insight into the design of the detector, reference has to be made to the basic ionization characteristics of the cabin air at low pressures. Figure 70 shows the typical characteristics of breakdown potential, (the potential at which ionization is initiated) versus the product of pressure times gap for a simple electrode arrangement of two flat plates in air. As seen, the curve reaches a minimum at a pd of about 0.53 mm Hg-cm, which corresponds to a minimum breakdown voltage of about 330 volts.

If this simple electrode arrangement were used as a leak detector, the operating characteristics would be as follows. Assume that the gap between the electrodes is one cm. and the applied potential between electrodes is 500 volts. Then, the pd product for which ionization occurs would be $\leq$ 2.1 mm Hg-cm and $\geq$ 0.23 mm Hg-cm. Since the electrodes are mounted outside the cabin, between the walls, the initial pd product, prior to a leak is less than 0.23 mm Hg-cm and no ionization occurs. When a leak occurs, however, the pressure between the walls rises. Since the electrode gap is one cm., when the pressure rises above 0.23 mm Hg, ionization occurs and current flows between electrodes which signals the warning system. If the pressure rises above 2.1 mm Hg, ionization will cease. The sensitivity of this particular electrode design is, then, 0.23 mm Hg. The sensitivity of this design can be increased by two means: (1) by increasing the applied potential, and (2) by increasing the gap. For example, if the potential were raised to 2000 V, and the gap remained at 1 cm, the minimum pressure required for ionization (i.e., the sensitivity) would be about 0.1 mm Hg. Or, if the gap were increased to 4 cm and potential remained at 500 V, the sensitivity would reduce to about 0.06 mm Hg.

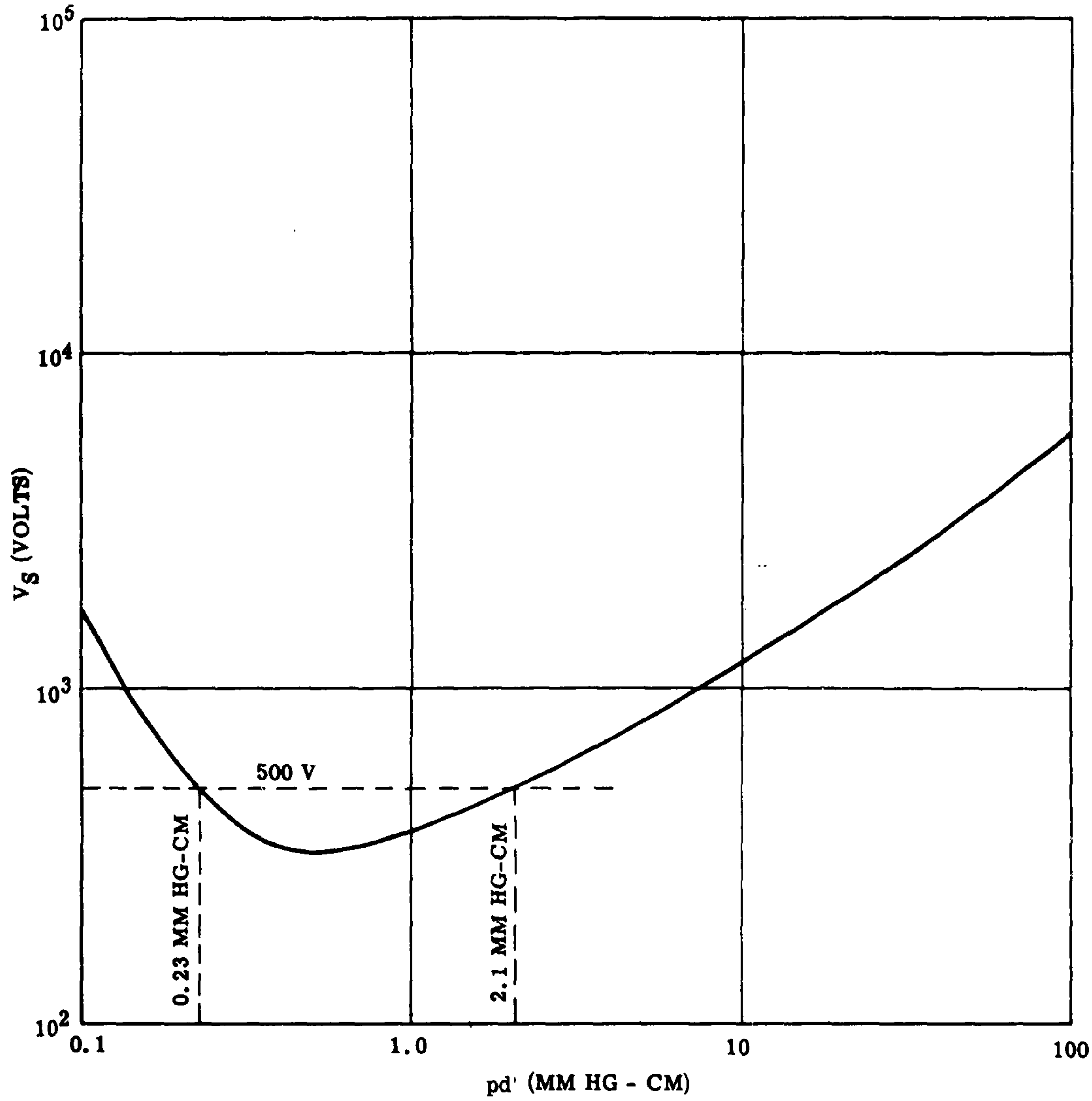


Figure 70. Breakdown Voltage Vs. Pressure X Gap for Parallel Electrodes in Air

From Data compiled by Carr, Ritz, Meyer, Holst & Koopmans

Since the desired sensitivity of the leak detector is on the order of 1×10^{-5} mm-Hg, it becomes obvious that a different detector design from the simple arrangement above is required. There are several factors which act to initiate the ionization of a gas. A quick look at these factors is offered as a basis for possible methods to enhance the ionization process and thus increase the sensitivity of the leak detection system.

The ionizing agents are:

1. Cosmic Rays - Cosmic rays possess an enormous amount of energy; consequently, they very readily ionize the air or gas through which they pass.

2. Radioactivity - Radiation given off in the disintegration of an element produces ionization in a gas.

3. X-rays - X-rays ionize gases in much the same way as cosmic rays and radioactivity. The process involves the conversion of electromagnetic energy into potential and kinetic energy of an ionized molecule.

4. Intense Electric Fields (Ionization by Collision) - The mechanism here involves the acceleration of charged particles (a few charged particles are present at all times in any gas) by an electric field until they have sufficient energy to produce more ionization in colliding with neutral molecules or atoms. These new ions then accelerate until they too have sufficient energy to cause ionization by collision.

5. High Temperatures (Thermal Ionization) - If a gas is heated to a high enough temperature the kinetic energy of the molecules will increase to the point where they will produce ionization in colliding with each other. The temperatures required for this are very high, 5000 to 6000° C.

6. Flames, Chemical Effects, etc. - Gas in the neighborhood of a flame exhibits a marked conductivity. Also, in many chemical reactions, such as the passing of air over moist phosphorous or bubbling through water, the air becomes ionized.

The above six ionizing agents are those which produce ionization throughout the body of a gas. There are other ionizing agents that are active only at the surface of a gas. These are important, however, for any production of free charges at the boundary of a gas will increase the net number of free charges in the gas and consequently its conductivity. At least one of the following ionizing agents is present in practically every case of gaseous conduction.

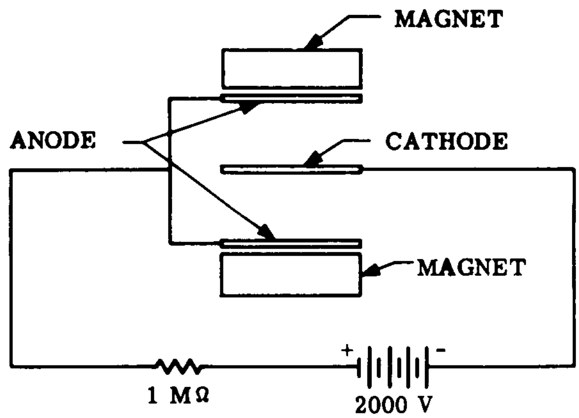
7. Photoelectric Emission - The incidence of light close to or in the visible region on some materials produces the emission of electrons from the surface of the material.

8. Thermionic Emission - When metals are heated to a sufficiently high temperature, they emit electrons.

9. High Field Emission - Under the influence of an intense electric field (hundreds of millions of volts/meter) the surface of a metal will yield electrons.

10. Secondary Emission - High speed particles have the ability to cause the emission of secondary electrons from the surfaces of metals with which they collide.

The cold cathode ionization gauge uses the ionizing agents of high field emission and ionization by collision to produce high sensitivity. A simple schematic of the system is shown below.



In this instrument, electrons are emitted from a cold cathode of zirconium, thorium, or any other type of active surface, under the influence of a high potential of about 2000V. The electrons are deflected by means of a magnetic field of about 370 oersteds so that the length of path taken by the electrons between cathode and anode is many hundreds of times the direct distance. Since it has previously been shown that the potential required for ionization is a function of pressure times gap (length of path), the magnetic field effectively raises the sensitivity of the gauge by increasing the gap between electrodes. In other words, with longer travel by the emitted electrons, they have an increased chance to collide with a gas molecule, thereby ionizing it, and producing ionization by collision. The total current flow between electrodes is the sum of the electron current plus the ion current and is proportional to the pressure (i. e., number of gas molecules present).

Commercial cold cathode ionization gauges generally have a sensitivity of about 1×10^{-7} mm Hg, but in one reported instance could be as high as 1×10^{-13} mm Hg. The upper limit of pressure sensitivity is about 5×10^{-2} mm Hg. That is, the gauge would conduct at pressures between 10^{-7} and 5×10^{-2} mm Hg. Above or below these limits conduction ceases.

There are types of ionization gauges, other than the cold cathode type described above, that might be applicable for the leak detector. One is a hot filament ionization gauge that substitutes thermionic emission for the high field emission. A hot wire supplies electrons, which, upon being accelerated to the anode collide with the gas ions. The positive ions are collected on a separate element called the ion collector, and this ion current is then proportional to the pressure. This type of gauge is more sensitive, generally, than the cold cathode type, and could detect pressures in the 10^{-10} mm Hg range.

It does not require magnets and operates at less voltage, also. However, it is not as rugged as the cold cathode gauge, and the hot filament can be "poisoned" or even destroyed by the presence of a chemically active gas such as oxygen. Filament burnout at pressures above 10^{-3} mm Hg is a potential problem also. For these reasons, the hot filament ionization gauge is less adaptable for use in flight hardware as a leak detector, although if higher sensitivity is ever required, it may again be considered.

Another type of ionization gauge, called the "Alphatron" uses a small quantity of radium to produce alpha particles that ionize the gas. Voltage requirements are quite low; however, ionization current is very small, requiring large amplification for readout or signaling purposes. For this reason, plus the obvious disadvantage of radioactivity requiring special provisions and handling, this detector is less suitable than either of the two described above.

As determined in the trade-off study in the preceding section, the leak detector should have a sensitivity of about 1×10^{-5} mm Hg. At this sensitivity, there is a reasonable balance between the area of coverage for each detector and the system weight and minimum detectable leak. Both the system weight and minimum detectable leak could be reduced, however, by increasing the detector sensitivity, if desired.

Figure 71 shows the conceptual design of the leak detector. The ring-shaped cathode is positioned within a semi-cylindrical anode. Parallel to, and on either side of the cathode are two permanent magnets, connected by a ferromagnetic semicircular ring which produces the magnetic field between anode and cathode. Since a 2000 volt potential is required between electrodes, a converter is required to step up the available voltage. With existing solid state techniques, the converter can be made quite small and lightweight. On this basis, it is desirable to supply each leak detector with its own converter; that is, design the converter and cold cathode detector as one integral package. This eliminates the need for extensive high voltage wiring as it keeps all the high voltage components within the detector-converter unit. Power supplied to each unit need be, then, only 28 VDC.

Figure 72 shows the DC to DC converter electrical schematic diagram. The 28 VDC input is switched by the two transistors to produce high frequency AC. The voltage is then stepped up in the

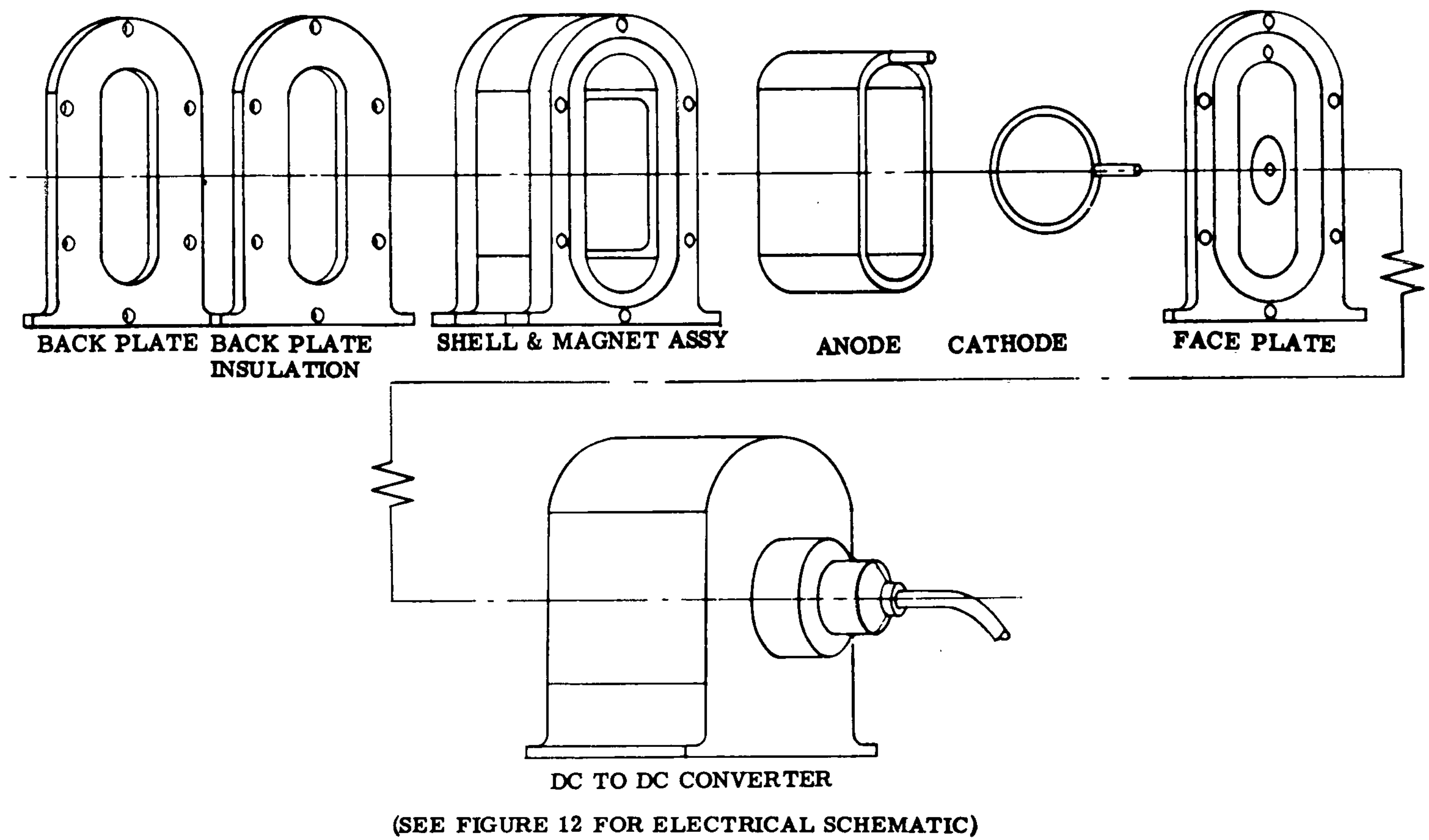


Figure 71. Leak Detector

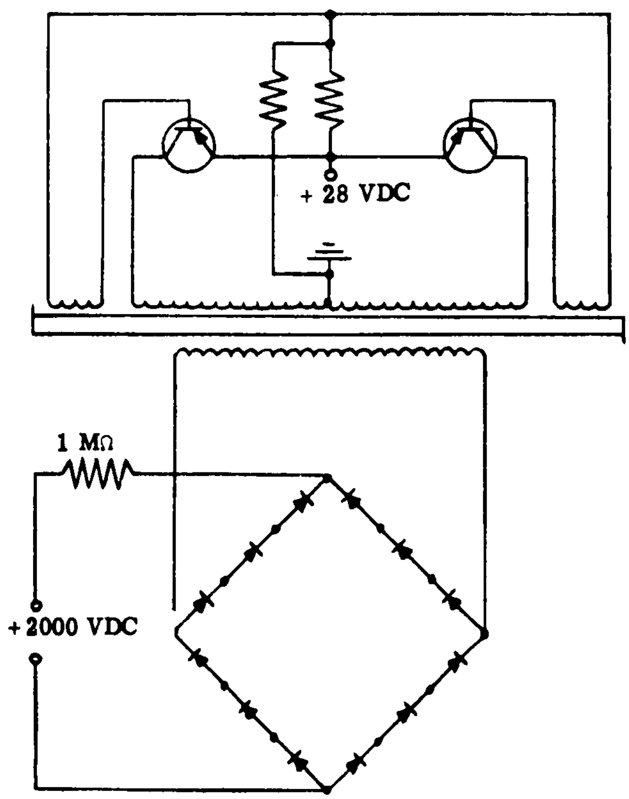


Figure 72. DC-DC Converter, Electrical Schematic Diagram

toroid transformer to 2000 VAC and rectified by the simple bridge rectifier to produce 2000 VDC. The high frequency AC keeps the transformer core size to a minimum, thus the overall weight is low (about 6 ounces). In addition, the weight of each detector would be about 8 ounces, so that the overall weight estimate for each detector-converter is 7/8 lb.

The no load (i.e., no leak) power requirements for the converter would be about 80 mw. This is required to make up transformer core losses and supply the bias and feedback current to operate the switching transistors. Maximum power is required in the presence of a large leak and would amount to about 4 watts. The actual power depends on the pressure present at the electrodes. The maximum current in the high voltage circuit is limited by the load resistor (1 M Ω) to a maximum of 2 ma to prevent an overload. Corresponding primary current is then, about 140 ma.

6.3 WARNING SYSTEM

The leak detector described thus far will generate a current in the electrode circuit upon initiation of a leak in the space cabin. A system is required that can utilize this signal to warn the crew of the presence of the leak. In addition, the system must in some way display to the crew which leak detector has been activated. In this manner, the general location of the leak will be known.

Two possibilities are apparent. The warning system could use as a signal either the rise in current in the primary (28 VDC) supply to the detector or the current generated in the high voltage (2000 VDC) electrode circuit. Difficulty would arise in the former case, however, because for a minimum leak, the rise in current in the 28 V supply would be small in comparison to the no-load current. Thus it is more desirable to use the ionization current as the signal.

A transistorized amplifier as shown in Figure 73 can be used to actuate a relay which, in turn, closes the warning display circuit. With no or negligible current between the electrodes, the voltage on the base of the transistors is insufficient to cause them to conduct. At a pressure of 10^{-5} mm Hg between electrodes, however, ionization occurs and will produce approximately 10μ a current in the electrode circuit. The 0.5 MΩ resistor then produces a driving potential of about 5 volts on the transistor base which is more than sufficient to effect conduction. Two transistors are needed to provide the current amplification required to operate the relay.

Two possible problem areas in this design require discussion. One is the possibility of normal, inherent spacecraft leakage triggering the detection gauge and hence the warning system. For vehicle number 1, the maximum allowable leakage is 1000 cc/min or 0.079 lbs/hr. Since there are 14 detectors spaced around the cabin, the average normal leakage per detector is about 0.006 lb/hr. Since not all areas of the cabin will exhibit the same leakage, it might be reasonable to expect that in one particular area, leakage exists at 5 times the average or about 0.030 lb/hr. Since this is above the minimum detectable leak, 0.0275 lb/hr, both the detector and warning system would be activated. While the chance for this happening is admittedly rare, it is relatively easy to correct by adding a variable resistor in series with the base of the first transistor. This would enable the transistors to fire at any preset threshold of detector ionization current. In effect, this lowers the sensitivity of the leak detector-warning system from actuating at 1×10^{-5} mm Hg to any desired higher value. In practice the variable resistors would be set during systems test for each individual detector to give the highest leak detection sensitivity without detecting the normal spacecraft leakage.

The other problem is that in case of a large leak, when the pressure at the electrodes rises above about 5×10^{-2} mm Hg, the ionization current would cut off. As presently conceived, this would deactivate

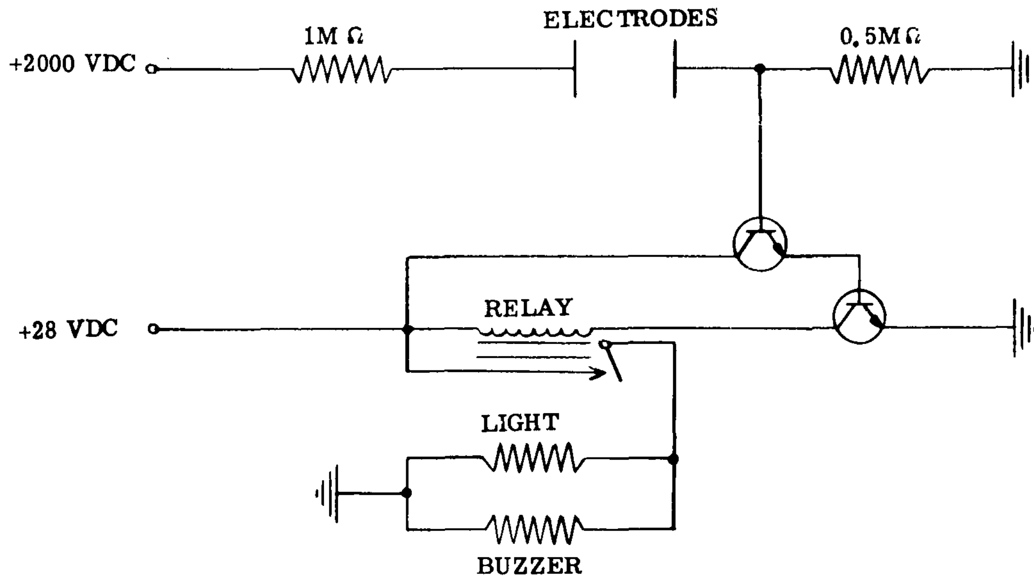


Figure 73. Warning System Schematic - Basic

the warning system also. This could be avoided in two ways. One, there could be a spark gap built into the ionization gauge that could maintain the discharge from about 10^{-2} mm Hg up to atmospheric pressure. This would be wired in parallel with the existing electrodes and the gap adjusted so the arc would not occur at lower pressures where it could interfere with the normal operation of the detector. At least one commercially manufactured Phillips gauge is known to include this feature. The other solution would be to utilize a relay that, once tripped, remains closed until manually reset. Thus the warning circuit would remain energized even if the ionization current ceased. This latter solution appears the easiest to accomplish. However, this promotes another aspect that bears mentioning. That is, it is desirable to check the adequacy of the leak repair by observing if the detector is still activated by leakage after repair has been made. It is conceivable that sufficient leakage could remain after repair to cause a greater than 5×10^{-2} mm Hg pressure at the detector, in which case the above observation could not be made. However, an analysis shows that the leakage required to create a pressure of 5×10^{-2} mm Hg at the detector at a minimal distance of four inches from the leak is on the order of 10 lbs/hr. The crew would have no trouble hearing audible noise from this magnitude leak so that in this case detector operation is not required. For lesser amounts of leakage, of course, ionization would occur and the repair could be readily evaluated.

The schematic of the warning system as modified appears in Figure 74. The warning system must also convey information on the location of the leak. This could be accomplished by locating each warning

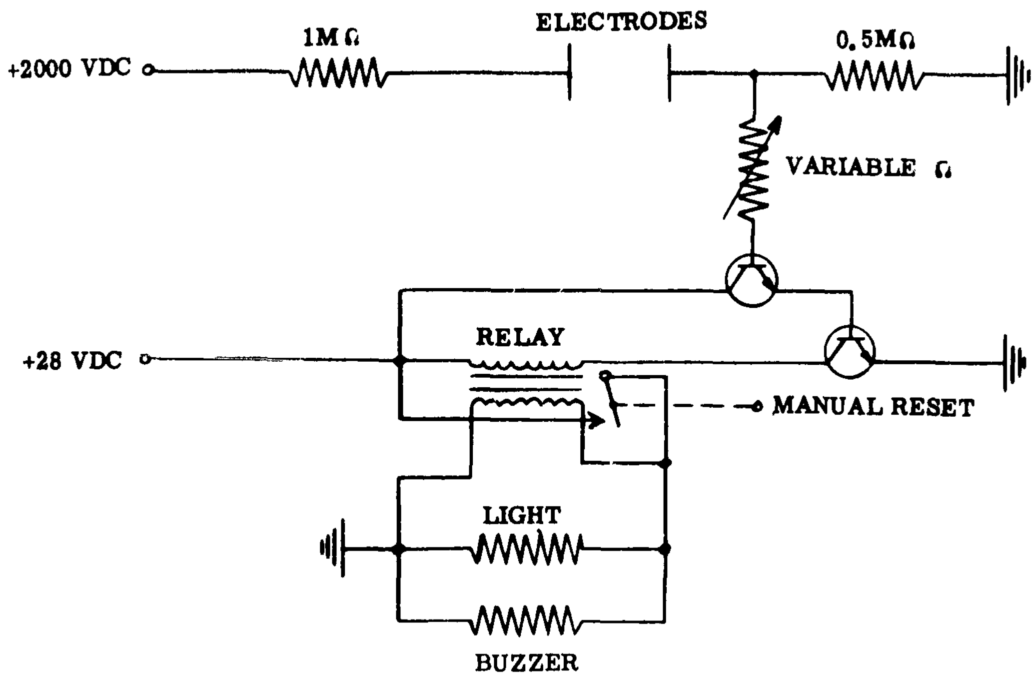
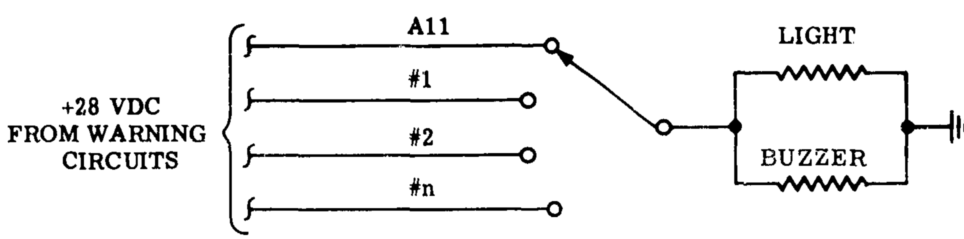


Figure 74. Warning System Schematic with Variable Leak Sensitivity and Continuous Alarm

light corresponding to a detector circuit in a central control panel. Then, when a leak occurs, an auditory warning can call attention to the control panel, and the lights would indicate which detector is activated. Because the number of individual lights could be large, however, it would probably be more desirable to use just one light and a multi-position selector switch. Prior to a leak, all warning circuits would be connected to the light and buzzer. Upon alarm, the switch could be rapidly run through the various positions to isolate the specific circuit activated. The schematic below illustrates this arrangement.



While the above system is adequate for determining the exact detector being triggered by a leak, there is perhaps a better method for conveying this information. This would be to locate a small light and buzzer on the inside of the cabin wall immediately in back of each leak detector. Thus, when a leak occurs, the crew would know instantly, by visual and audible warning, which detector is actuated, and where this detector is located on the cabin wall. They can then proceed directly to the proper area for repair. In the case of the former system with a central warning panel the crew would know which detector is firing (#1, or #2, or #3, etc.), but would have to rely on a chart or memory or other display for information on the location of the particular detector. In the case of a multi-compartmented space vehicle, where the damaged compartment may be unoccupied at the time, a combination of these two systems is required. A central control panel would indicate the compartment leaking, and further investigation by the crew would determine the area damaged.

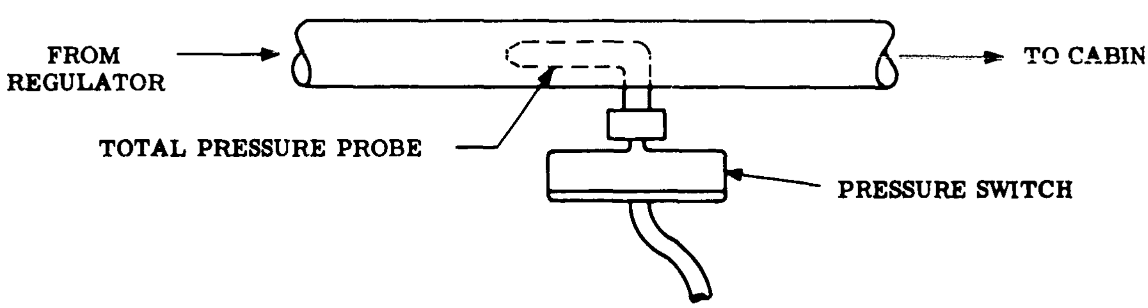
Thus, for the ideal system, the warning lights and buzzers will be located in units mounted to the inside of the cabin wall at the center of the area protected by the associated leak detector. Also located in this unit will be the sensitivity adjustment (variable resistor, see Figure 74) for the warning system, and the manual reset for the relay as well as the system test switch, and microammeter jack which will be explained later. For small leaks that require concentration by the crew during the location process or that may not require immediate repair, the buzzer, after serving as an attention-getter, may become quite irritating. Therefore, a switch will also be provided in this wall mounted unit that will turn off the buzzer.

As mentioned previously, additional information is required as to the relative magnitude of the leak. Three relative sizes need be known: (1) small leaks, where repair can be made at the convenience of the crew, (2) larger leaks where immediate repair is required, and (3) leaks of sufficient size to cause cabin decompression. The dividing line between the second and third category has already been established as equivalent puncture sizes of 0.25 inch diameter for vehicle #1 and 0.9 inch diameter for vehicle #2. The dividing line between the first and second category is rather arbitrary, however. A reasonable method of choosing this value is to first assume that a small leak will be repaired after a maximum delay of one hour. Second, for vehicle #1, assume that a loss of one pound or more of gas supplies within this one hour delay is excessive, and therefore, the leak should be repaired immediately. For vehicle #2, the same assumption can be made for a loss of two pounds of atmospheric gases. Then, the dividing line between categories one and two become leaks of 1 lb/hr and 2 lb/hr for vehicles 1 and 2, respectively. Table 9 illustrates the parameters chosen.

TABLE 9. LEAKAGE REPAIR PARAMETERS

	ACTION		
	Cabin Decompression	Repair Quickly	1 Hr. Delay in Repair Acceptable
Vehicle #1			
a) leak rate (lb/hr)	>25.1	$\leq 25.1; >1$	≤ 1
b) equivalent diameter (inches)	> 0.25	$\leq 0.25; >0.050$	≤ 0.050
Vehicle #2			
a) leak rate (lb/hr)	>306	$\leq 306; >2$	≤ 2
b) equivalent diameter (inches)	> 0.9	$\leq 0.9; >0.070$	≤ 0.070

A simple arrangement for a warning system to alert the crew of a cabin decompression is possible due to the large increases in leakage and demand on the atmospheric gas supply system. With the most probable design of the atmospheric control system, the diluent, nitrogen, would be supplied by a total pressure demand regulator and oxygen would be supplied through valves operating in response to the oxygen partial pressure. When a puncture of sufficient magnitude occurs to cause the cabin to decompress, the initial immediate response of the nitrogen supply total pressure regulator is to open wide in an attempt to maintain the cabin total pressure. This creates a nitrogen supply flow rate many orders of magnitude above the normal flow. A pressure switch attached to a total pressure probe in the exit of the nitrogen supply line can be used to sense this increased flow as shown in the sketch below.



The switch and/or total pressure probe can be calibrated to close at the flow rates created by the minimum size leak that requires a cabin decompression. Once closed, the switch will be utilized to sound the decompression warning to alert the crew, and close the atmospheric supply systems so that no further loss of gas ensues. Thus, this warning system acts independently of the warning systems attached to the leak detectors.

Obviously, other decompression warning systems could be devised. For example, upon signal of a leak, the atmospheric gas supplies can be turned off, and a cabin total pressure sensor can be used to determine the leakage rate. This system would be considerably more complex, however, and thus not as desirable.

A separate warning system to differentiate between the very small leaks that do not require immediate repair and those that do require immediate repair is not as easy to devise. A flowmeter in the nitrogen supply line could be used to detect abnormally high flow rates. However, the nature of the supply system makes this difficult because the nitrogen flow rate is not, over any short period, dependent on the nitrogen usage or leak rate but depends on the total pressure. The total pressure, in turn, is affected by the cabin leak rate, oxygen consumption rate, and oxygen supply system rates. Thus a true nitrogen use rate or leakage rate cannot be determined in this way. Measuring the cabin total pressure drop over a time period with no additional gas being supplied is another means for determining leak rate. For vehicle #1, with a leak rate of 1 lb/hr, the time required for a 1 mm Hg cabin pressure drop is 2.3 minutes. For vehicle #2, with a leak of 2 lbs/hr, this time is 4.3 minutes if the compartments are closed, or 12.1 minutes if they are open (i.e., for the entire vehicle volume). Besides being fairly complex, this system would also be influenced by the variable metabolic oxygen consumption of the crew, but could be designed, nevertheless, to work within rough limits.

A far simpler and easier way to differentiate between these relative magnitude leakages is to utilize the crew themselves. Since the dividing line between the two leakage categories lies near the threshold value of leakage needed to produce audible noise, reception of this noise by the crew can be used to assess the leakage magnitude. This method, while not too accurate, is recommended because of its simplicity and should be suitable for the task.

Summing up, the warning system would operate as follows: Upon detection of a leak by the leak detector, the light and buzzer mounted on the cabin wall associated with this particular detector would be activated. This would give instant warning, plus enable the crew to quickly and easily locate the damaged area. It should be pointed out that, in this arrangement, some of the warning lights could be hidden from view by equipment. If this is the case, either the warning "module" or light could be mounted in front of the equipment, but still in the same area, or the buzzer alone could be used to indicate quickly the general location of the leak. In the case of vehicle #2, a buzzer and light would also be activated in the central control panel, showing which compartment was damaged (i.e., is leaking). If the leak is of sufficient magnitude to cause cabin decompression, the decompression warning system will be activated almost instantaneously. The warning will be a loud, raucous noise, as produced by a klaxon horn, that will leave no doubt as to the action desired (i.e., obtain secondary pressure protection immediately). If no decompression warning is given, one of the crew will turn off the buzzer in the leaking area in question. If the leakage can be heard, (i.e.,

a steady hiss) the repair must be made immediately. If not, a delay in repair of up to one hour can be tolerated.

6.4 LOCATION OF LEAK

Precise location of the larger leaks will be readily apparent from a visual observation of the cabin wall surface. These leaks would include all punctures of the cabin. Smaller leaks from cracks and seal failures will be located by playing a small jet of helium gas over the suspected area, and noting the response of the leak detector ionization current. Seals in the damaged area will be inspected in this manner first, because the probability of leaks due to faulty seals is much greater than that due to indiscernable cracks or pinholes.

The helium will be stored in a high pressure storage tank as a gas at 3000 psi. A reasonable maximum discharge rate, when used, is 0.3 lbs/hr. A regulator will be fitted to the exit line to limit the flow to this amount. The regulator will also be capable of reducing this flow rate to any lower value which may be needed for precise location of the leak.

A jack for the microammeter will be provided in the small control panel mounted on the wall. In practice, the crew would plug a microammeter into the jack and note the ionization current. The helium regulator would then be opened wide (0.3 lbs/hr) and the gas jet played over the suspected seals. When the helium passes over the leak, the ionization current will drop. By slowly reducing the helium flow and observing the microammeter, the leak can be pinpointed.

To locate a leak in any one area, it is estimated conservatively that a maximum of 15 minutes supply of helium, or 0.075 lbs., is needed. For vehicle #1, with a 14 day mission, a reasonable maximum of two such inspections are required. Thus, 0.15 lbs. of helium are required. The weight of the tank plus helium plus regulator would be, then, about 2.2 lbs. For vehicle #2, a maximum of 8 such inspections may be required. For this vehicle, the total weight is 8 lbs. This total can be divided by carrying the helium in two or more tanks so that they can be hand-held with no difficulty.

The leak detection, location, and warning system is shown schematically in Figure 75 and illustratively in Figure 76. The only aspect of the system that has not been discussed previously is the provision for system test. A switch is provided for this purpose in the wall-mounted panel for each detector. Flipping this switch will close a relay and connect 100 MΩ resistor across the detector electrodes, thus simulating the ionization current. The power supply, converter, and warning system can then be observed for proper operation.

6.5 REPAIR OF LEAK

The best method of repairing seals is to apply a liquid adhesive sealant to the juncture of the seal surface and cabin wall. The sealant should cure to form a impermeable thin film or sheet between the cabin atmosphere and the seal itself. In a normal environ-

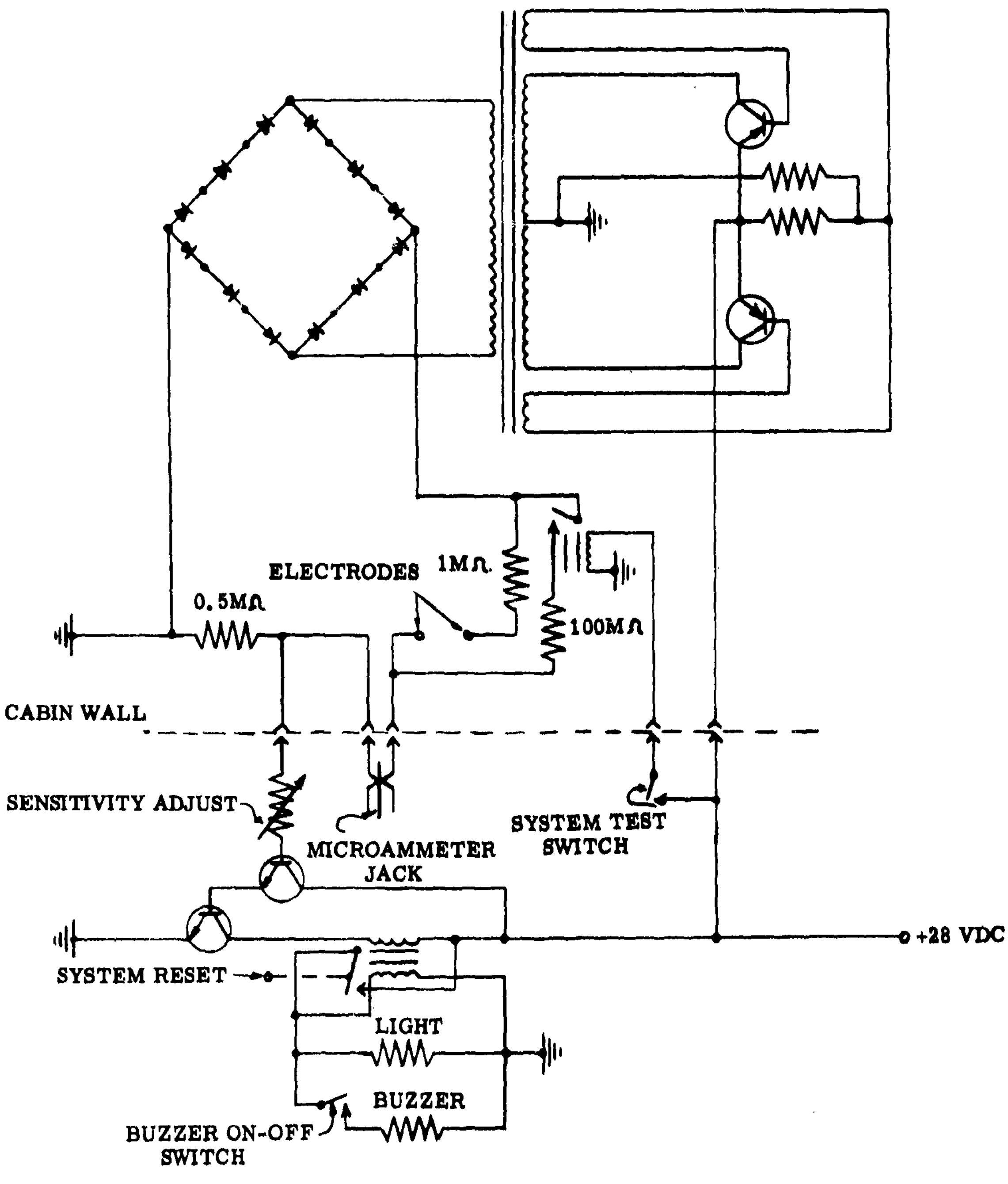


Figure 75. Leak Detection, System Schematic

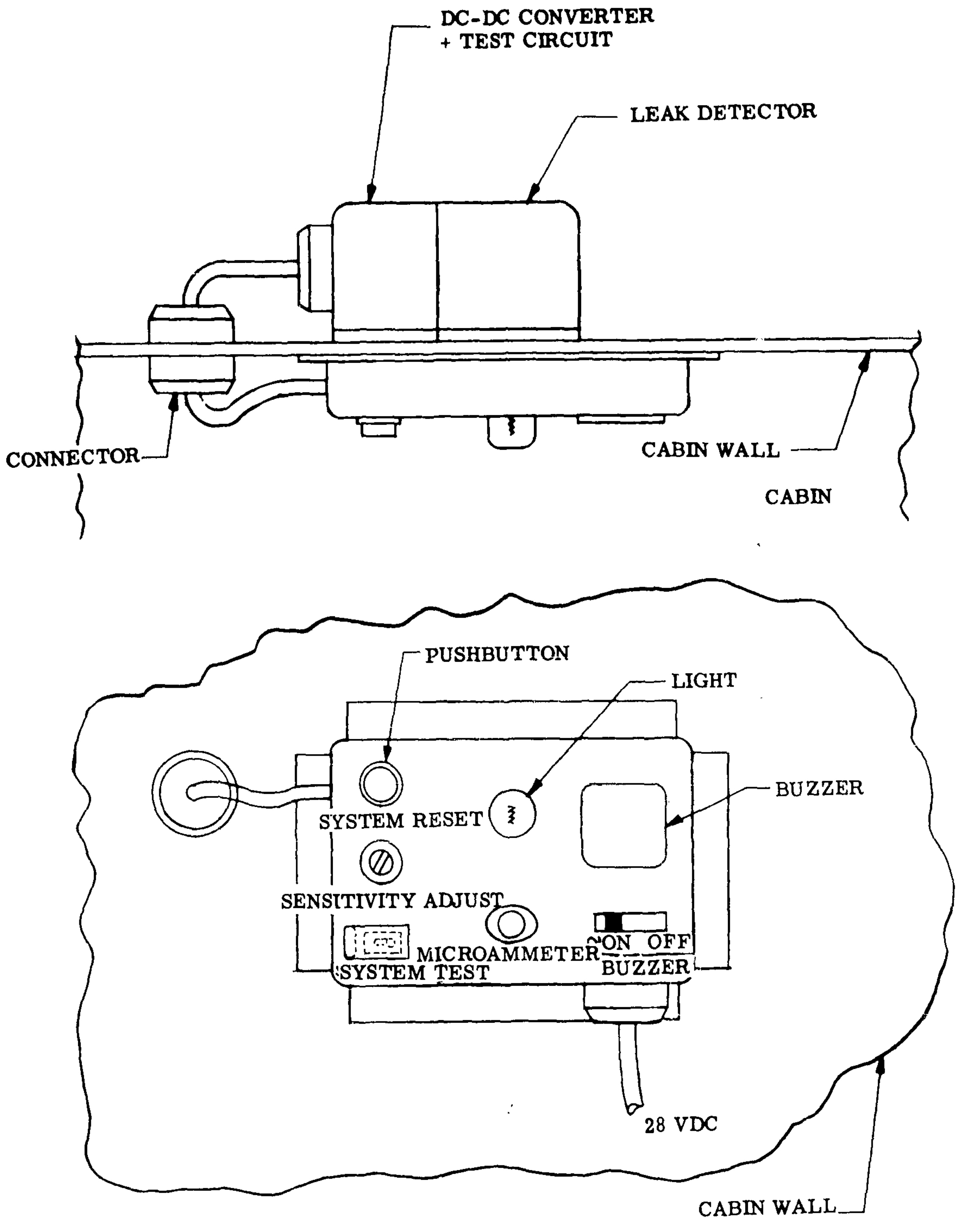


Figure 76. Leak Detection System Arrangement

ment, the natural method of applying this sealant would be with a brush. In a zero-g environment, however, this method would not be very practical because of the possibility of spilling the sealant. A special applicator can be designed to overcome this problem, by making the brush (or felt or similar type pad) an integral part of the sealant storage reservoir.

This concept is represented in Figure 77. The sealant is stored in a small cylindrical tube. The tube is flattened at one end with the brush applicator held at the tip. The other end is a collapsible plunger with which the operator can force the liquid sealant to the brush. A cap can be screwed over the brush when the tool is not being used. This applicator is similar in operation and size to a conventional hypodermic syringe, except that a brush is used instead of a needle.

The sealant material should be a one part compound that has good adhesion to metals and cures to form a tough, resilient film. Most liquid sealants of this type cure by solvent release and use solvents which are toxic when allowed to concentrate. The most likely candidates for the choice of the material therefore appear to rest with the adhesive sealants composed of emulsions and dispersions of a number of thermo plastic resins in liquids which contain little or no solvent. These dispersions and emulsions eliminate the need for these solvents, and they have an adequate solids content. They can be compounded with modifying agents to offer the advantages of neutrality, almost complete freedom from odor, good keeping qualities, tolerance to freezing and thawing, craze resistance and flexibility. Addition of tackifying resins and combinations of resins can be used to increase the adhesion to metals. These adhesives generally set by the evaporation of water. They are limited in high temperature applications because of their thermoplasticity; however, suppliers and users are working now to produce thermosetting types (Ref. 17).

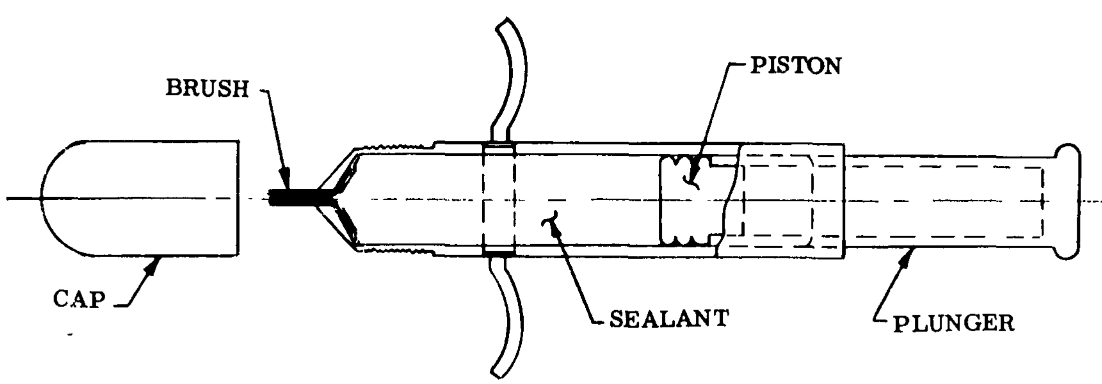


Figure 77. Liquid Sealant Applicator

The above water emulsions would have a quick initial set, although time for complete cure would be relatively long since it depends on complete removal of the water. Faster cures can be obtained by using a more volatile liquid. Polyvinylbutyral in ethyl alchol is one example. This would cure to form a plastic coating. Another possibility is corn protein (zein) in alcohol and water. Ethyl alcohol should be satisfactory from a toxicity standpoint. The use of liquid sealants based on the synthetic rubbers dissolved in ethyl acetate are other candidates. Ethyl acetate has some undesirable toxic effects, however, so this should be checked carefully.

The exact choice of the sealant would be determined by a test program, which would evaluate the various candidates for durability, permanency under shock, vibration, and the space environment, reliability of sealing, toxicity, etc., and is beyond the scope of this study. An outline for such a test program is given under recommendations (see Section 6. 6).

While the above sealant is adequate for repair of all fixed seals, including seals for emergency hatches that may have to be broken, it will not suffice in a few specialized cases. These would be for repair of cabin seals for rotating or reciprocating shafts where the shaft moves in relationship to the wall. Typical designs for these seals are shown in Figures 78 and 79, taken from reference 18. As seen, any attempt to apply sealant to the juncture between shaft and cabin wall would not allow the shaft to move.

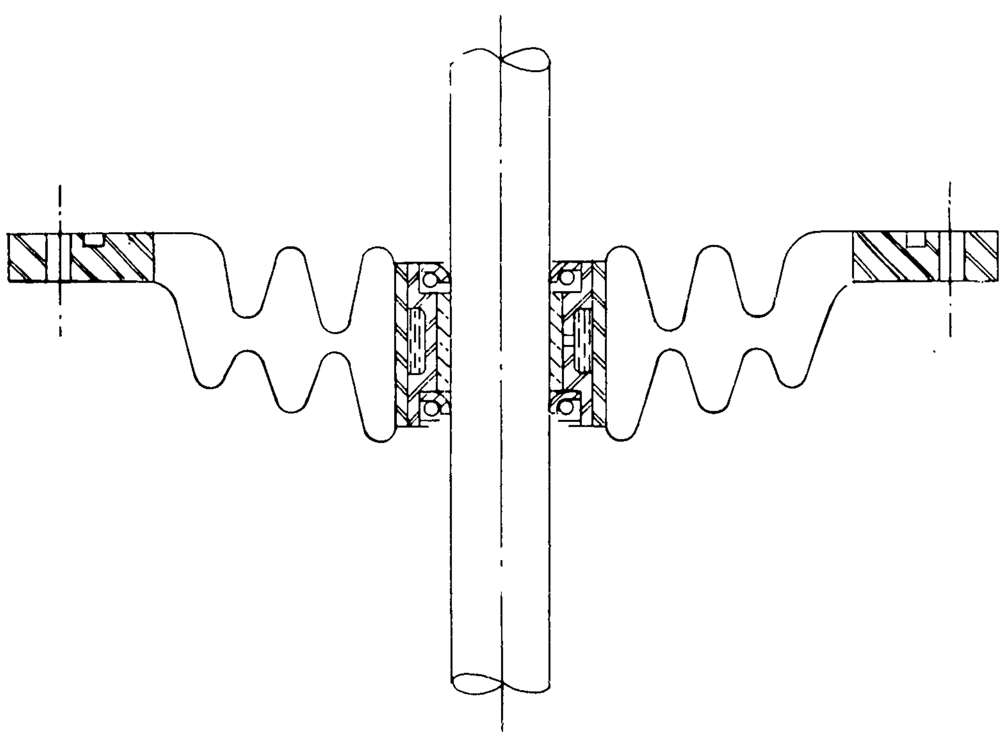


Figure 78. Rotating Shaft Seal (Ref. 18)

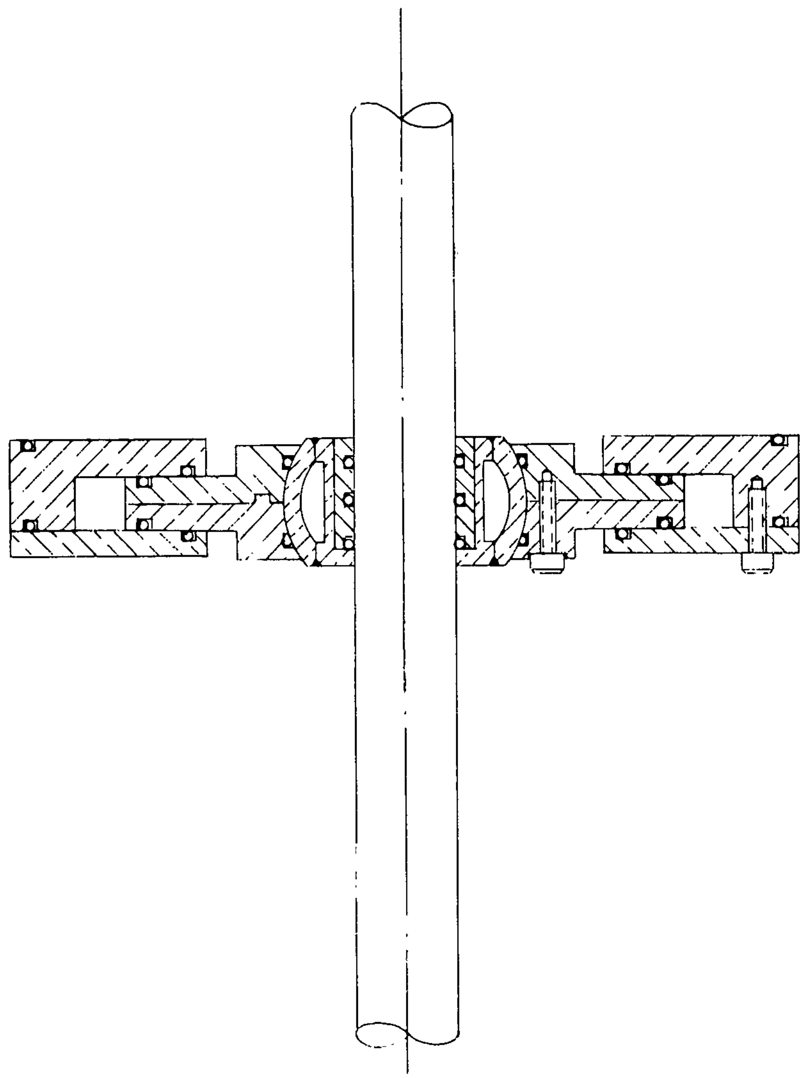


Figure 79. Reciprocating Shaft Seal (Ref. 18)

There are several solutions for the repair of such seals. One is to disassemble the seal and replace it. This is undesirable because it would necessitate decompressing the cabin, with resultant loss of cabin atmospheric gases. Another solution is to render the shaft immobile and seal the shaft-cabin junction with the liquid sealant. This is undesirable, of course, because it renders the rotating or reciprocating component inoperable and thus its use is lost to the overall mission. A third solution would be to seal the surfaces with a high vacuum grease that would enable the shaft to move and yet prevent leakage. This solution is liable to be unreliable due to loss of the grease to vacuum or slight displacements of the grease which would allow the leakage to continue (i. e., it would have less than complete permanency). A fourth solution would be to design the shaft and seal components so that an additional seal can be added without replacing the original seal. This seal and its retaining structure could be bolted to the existing components and provide the sealing effect required. This concept does not have the disadvantages of the first three methods. It should be emphasized, therefore, that in the detail design of seals for moveable shafts, provisions should be made for repair of these seals,should failure occur.

Repair of cracks and punctures can best be achieved with a mastic or putty type adhesive sealant. Such adhesives are composed of thermoplastic resins like polyvinyl acetate and casein, or rubbers like neoprene or GR-S. They are emulsified in water, then thickened to a putty with fillers and gelling agents. Various modifications can be made to improve the adhesion to metals by incorporating tackifying resins and combinations of resins. The advantage of using this type adhesive is the absence of volatile solvents and noxious fumes from chemical hardening agents which would permeate the cabin atmosphere and cause irritation and illness to the crew. The conventional room temperature setting thermo~ets often contain glycidyl ethers as viscosity and flow improvers and their vapors cause symptoms of toxicity. However, epoxy adhesives and sealants can be formulated with non-toxic chemicals such as certain boron salts and the amine adducts. Adducts are amines that are pre-reacted with a portion of epoxy resin and thereby rendered essentially innocuous.

This repair method is ideally suited for repair of those punctures where time cannot be allowed for rework of the damaged area. That is, it can be readily molded over sharp, protruding edges, over irregularly shaped holes, and can also reach tight corners. Because of this, the putty sealant has to be capable of repairing punctures up to the size that will cause a cabin decompression. Since these punctures can be quite large, up to 0.9 inch diameter for vehicle #2, the putty will have to be quite stiff to resist extrusion through the hole prior to curing.

The putty should be a one part compound also. That is, no mixing of components is required prior to application. The putty should cure to form a tough, durable, resilient seal. There may be some

difficulty experienced in compounding a one part sealant that will meet all of the requirements, however. For example, the requirements for the original stiffness and consistency needed to resist extrusion may not be compatable with the requirements for good adhesion and room temperature cure. In this case, a two part curable sealant material will have to suffice. It would be easier to formulate a two component system of resins and catalysts or hardeners that would meet all of the requirements for toxicity, permanency, adhesion, etc. To seal the leak initially, and thus prevent excessive loss of cabin atmosphere, the leak could be temporarily plugged with a non-curing putty. Then, the final two part compound could be mixed and made ready. If the temporary putty is durable enough (i. e., resistant to extrusion and to the space environment), this final sealant could be applied over the temporary repair. If not, the temporary plug could be removed, and the final sealant emplaced and allowed to cure to form the seal.

Special storage and mixing containers for the two component system would not be difficult to devise. One simple method would be to store the putty sealant in a small,flexible plastic bag (enough for one application) within which would be a vial containing the catalyst or hardener. When required, the bag would be squeezed and the vial broken to release the catalyst. The bag would be kneaded with the fingers to mix the two components together. When thus mixed, the bag would be torn open and sealant removed and applied.

Repairs for larger punctures than those met by the putty sealant will be made with the cabin decompressed and the crew in pressure suits. Two types of repairs might be called for: (1) a puncture in an area free of obstructions would call for the use of a self brazing plug, (2) a puncture in a tight corner would require that a metal patch be fastened over the hole. The latter requires the use of the putty sealant for filling in the cracks and chinks between the patch and the wall for those edges that cannot be mechanically fastened.

In either case, rework of the damaged area is required prior to affixing the repair. In the case of a self-brazing plug, the puncture must be cleaned out till it is almost round. The final cutout must of course remove all bent edges and cracks that may extend radially from the puncture. If a motor driven tool is available, the puncture can be reamed out quickly and easily. The type of tool envisioned would be a battery-operated, hand-held tool similar to an electric drill in which a reamer could be inserted. If a motorized tool is not available, then a pair of nibblers will have to be provided. This is a hand tool with which the puncture can be progressively cut out. This, of course, would be slower and harder work for the crew than would be the case with a power-driven tool. Other tools required would be a file for removing burrs, and vise grip pliers which would be useful for bending the sheet metal wall. A screwdriver or wrench would also be needed to tighten up the plug prior to brazing (see Figure 80).

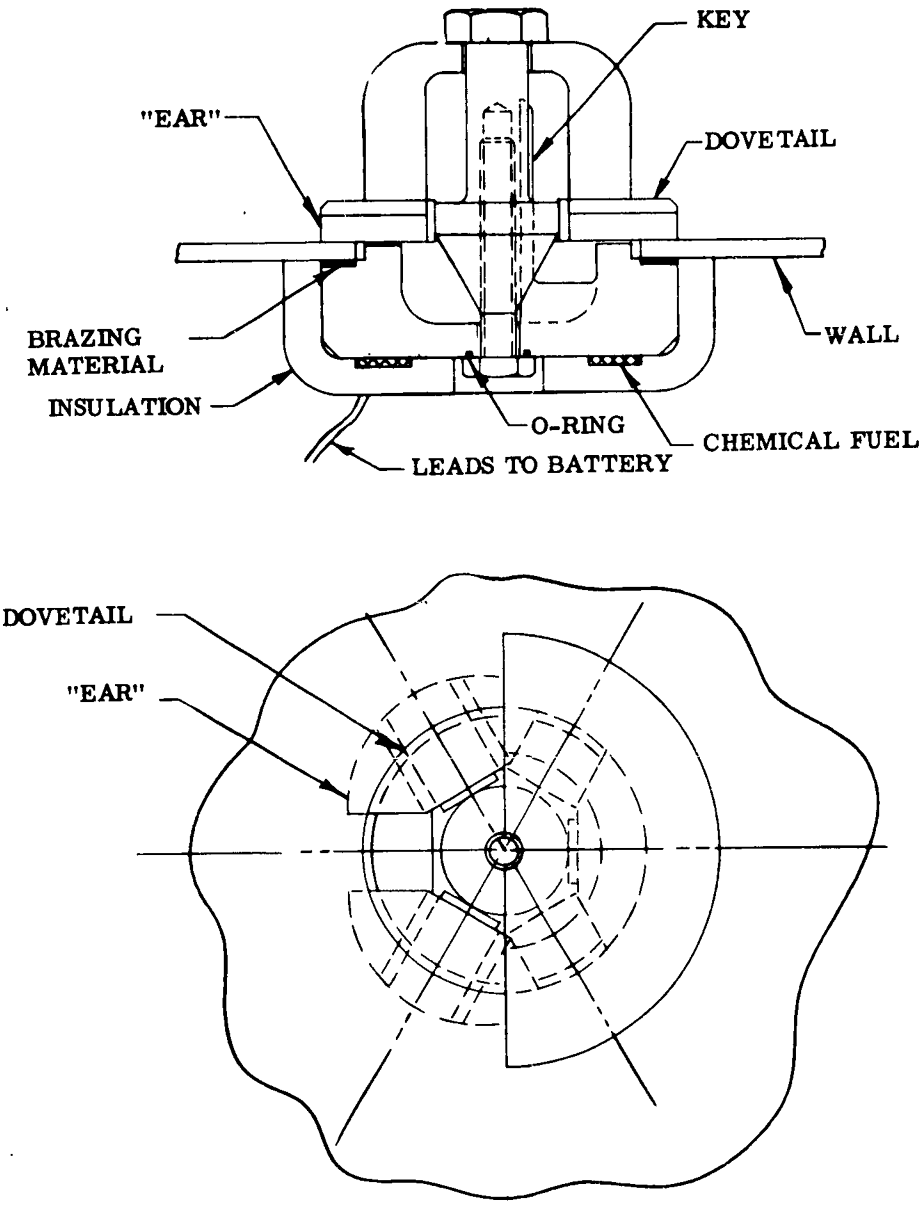


Figure 80. Self-Brazing Plug Design

For the sheet metal patch, a drill would be necessary to bore the holes for the fasteners. The patch itself could be cut to size with the nibblers, if power driven tools are not available. The patch should be aligned, drilled and fastened from the center out to obtain a close fit to the wall contour. Other tools required would be a center punch and hammer, and a wrench for the fasteners.

The above assumes that the cabin wall is a single welded sheet. It could, of course, be a honeycomb sandwich construction, in which case rework with hand tools could be very difficult. In this case, it would be necessary to provide the crew with power tools if repair of these large punctures is to be provided. It is quite probable that these tools would be required for other maintenance tasks such as assembly work, solar array repair, heat shield repair, etc., in which case they would be available for leak repair also.

Just a word on the zero g environment. The worker will have to be stabilized in position in order to conduct these repairs. This could be accomplished by a suitable harness that would anchor the man to the wall, or by a back pack type of stabilization system. Both hands should be free to work on the repair. Special torque-free tools must be used. It will suffice to say that these techniques are not unique in the repair of leaks, but enter into many phases of spaceflight and are being solved as separate problems.

A proposed design for a self-brazing plug is shown in Figure 80. The plug is designed to be inserted in the reamed out hole in the cabin wall, and tightened to form a good fit between plug and wall. This eliminates the misfit that might occur due to wall contour as the wall is formed slightly to fit the plug. For insertion into the hole, the dovetailed "ears" are retracted toward the center of the plug. Once inserted, the bolt is tightened. This draws the tapered plug inward, extending the "ears." A key prevents the assembly from turning. Further tightening draws the plug and wall together to form a snug fit.

Once fitted, of course, the electrical leads are touched to a battery and the plug is automatically brazed to the wall. An o-ring serves to seal the bolt. The insulation can be removed after brazing in order to check the quality of the repair. Several different size plugs will be required to cover the range of punctures that could occur. For vehicle #1, 1, 2 and 3-inch diameter sizes should suffice. For vehicle #2, 3 and 4-inch diameter plugs should reasonably cover the most probable punctures. One plug in each of these sizes is all that is required since the probability of sustaining two large punctures in one mission is very low. Also, in a pinch, a large plug could be used to seal a smaller puncture, it the smaller plug has been used, or a metal patch, normally used for the tight corners, could be utilized.

The metal patch type of repair requires more time for installation than the plug but is more versatile. The patch itself should be cut from stock at the time of repair to fit the particular situation. The puncture is then cleaned up and the patch fastened to the wall. The putty sealant should be used to form a gasket between the patch and wall and also fill in any chinks left in the patch due to the tight installation.

Any of these repairs can be checked for adequacy by the leak detection system as outlined previously. This insures the reliability of sealing (i. e., insures that the leakage will be completely stopped).

Table 10 presents a summary of the leak repair materials required. Approximate weight and volume requirements are given for reasonable supplies of the materials.

TABLE 10. LEAK REPAIR MATERIAL REQUIREMENTS

Material	Vehicle #1		Vehicle #2	
	wt (lbs)	vol (in^3)	wt (lbs)	vol (in^3)
1. Liquid sealant and applicator	0.3	8	0.7	20
2. Putty sealant, stiff, non-curing	0.1	2	0.6	10
3. Putty sealant, two part compound, curable	0.1	2	0.6	10
4. Self brazing plugs	1.5	60	1.5	60
5. Patch material and fasteners	0.9	9	2.5	25
Total	2.9	81	5.9	125

6.6 CONCLUSIONS AND RECOMMENDATIONS

As is readily apparent from the preceding table, the major portion of the total system weight is in the leak detection, location, and warning systems, with but a small percentage dependent on the leak repair material weight. The leak detectors are the single largest item of weight. Thus, in attempting to reduce the system weight the leak detectors should be examined first, since the largest potential weight saving can be gained in that area.

In the present design, the number of separate detectors (and hence, also warning system modules) was determined by the weight trade-offs of Figures 53 and 54 in the preceding section. This trade-off is not strictly applicable now since the system has grown. In the previous trade-off, the system weight was based on the weight of the leak detector and converter plus a two-pound fixed weight. This

weight per detector should include the weight of the warning unit module (four ounces), the system test circuitry (one ounce), plus the fixed weight of the helium location units, the leak repair materials and miscellaneous items. The decompression warning system has been omitted because this system should be included in the spacecraft system regardless of whether a leak repair system is provided. The system weight for vehicle No. 1 is 1.19 n + 6.1 lbs where n = the number of detectors. Similarly, for vehicle No. 2 the system weight is 1.19 n + 17.9 lbs. (For a breakdown of the fixed weight, see Table 11.) The system weight can now be traded off against the minimum detectable leak to find the operating parameters of the system in a manner analogous to that shown in Section 5, Figures 53 and 54. Figures 81 and 82 show the variation in the system parameters with trade-off time for vehicles 1 and 2. The point of operation can now be chosen as those parameters corresponding to the mission durations. This establishes the minimum detectable leak as that leak rate which, when multiplied by the mission duration, equals the system weight. It also means that detection and repair of smaller leaks would cost more, weightwise, in system weight than if the leak were allowed to continue, and detection and repair of larger leaks results in a weight saving.

TABLE 11. SYSTEM WEIGHT, VOLUME AND POWER REQUIREMENTS

Item	Vehicle #1			Vehicle #2		
	Weight (lbs)	Volume (in^3)	Power (watts)	Weight (lbs)	Volume (in^3)	Power (watts)
1. Leak Detector, Converter & Warning Units	10.7	216		76.2	1536	
power no leak			0.7			5.1
power leak (max)			9.6			14.0
2. Helium & tanks, reg., lines, etc.	2.2	130	---	8.0	500	---
3. Decompression warning system	2.0	80	25.0	8.0	320	30.0
4. Leak repair materials	2.9	81	---	5.9	125	---
5. Miscellaneous	1.0	10	---	4.0	40	---
subtotals	18.8	517		102.1	2521	
power - no leak			0.7			5.1
power - leak (max)			34.6			44.0
6. Power weight & volume penalty*	.4	26		11.5	753	
TOTAL	19.2	543		113.6	3274	

*Assumed as 100 lbs/KW + 1.5 lbs/KW-hr; and 2.1 ft^3/KW + 0.055 ft^3/KW-hr for a fuel cell power source.

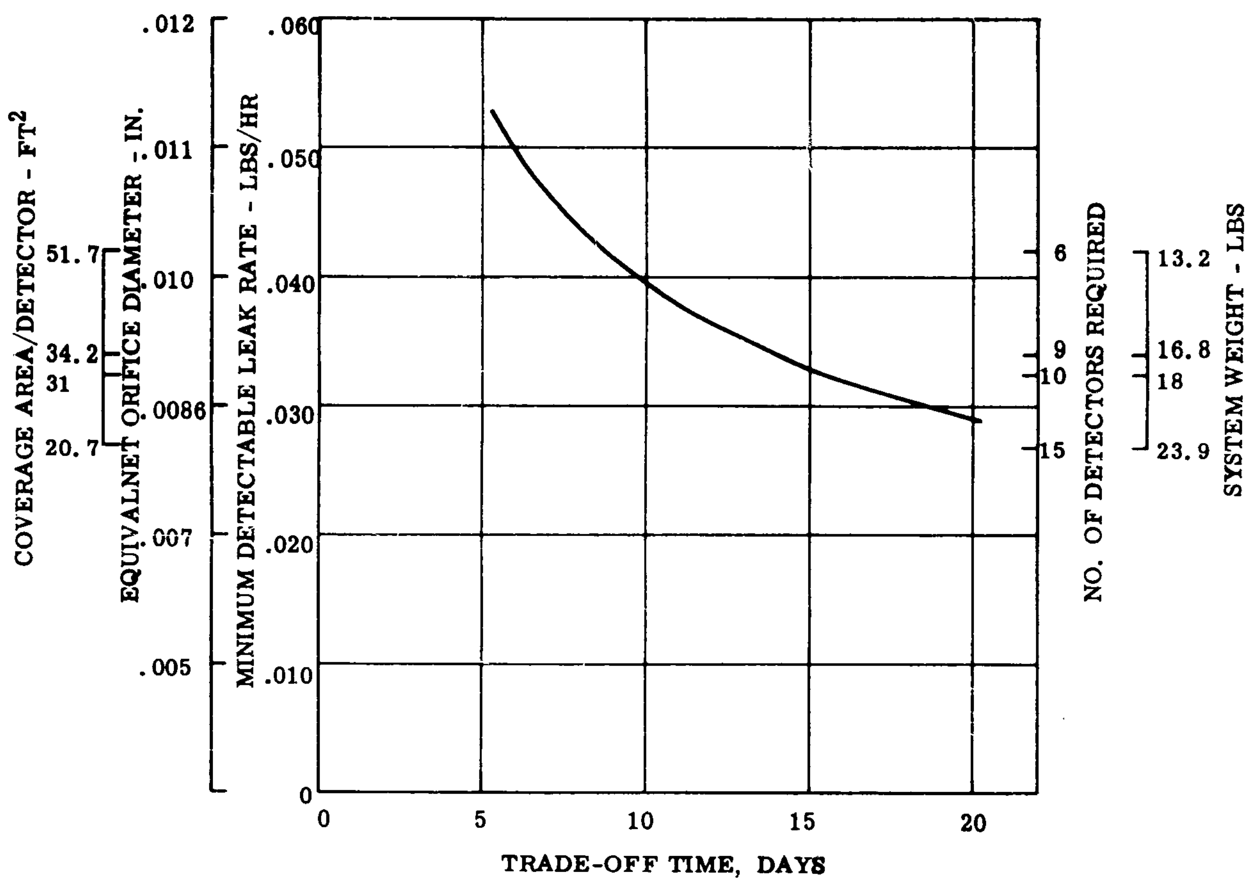


Figure 81. System Weight Trade-off, Vehicle No. 1

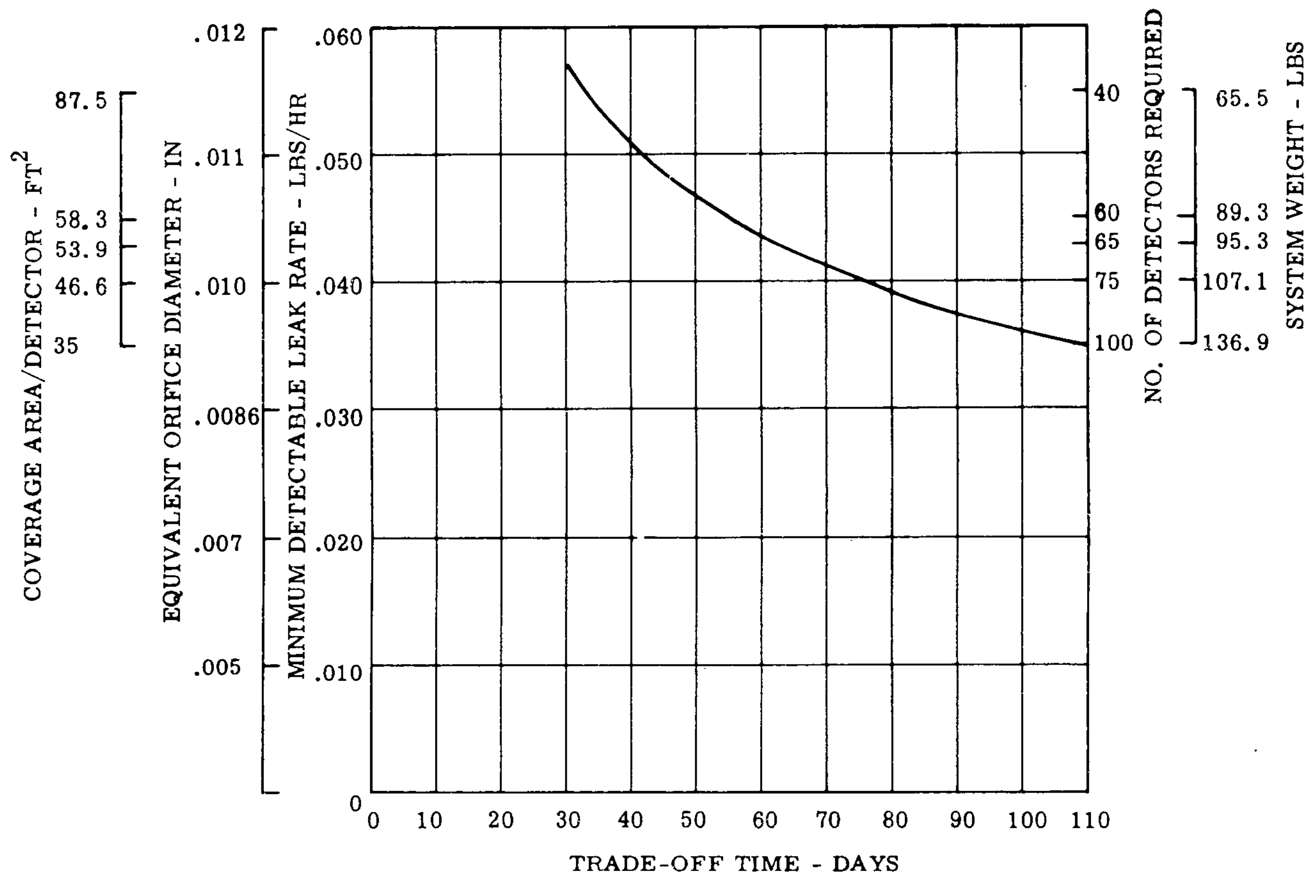


Figure 82. System Weight Trade-off, Vehicle No. 2

The new operating parameters for the system are then:

Vehicle #1

1. Minimum Detectable Leak - 0.034 lbs/hr

2. Number of Detector and Warning Units - 9

3. Coverage Area/Detector - 34.2 ft^2

Vehicle #2

1. Minimum Detectable Leak - 0.0435 lbs/hr

2. Number of Detectors and Warning Units - 64

3. Coverage Area/Detector - 54.6 ft^2

Based on the above system, a new weight estimate can be made. This is shown in Table 11.

The parameters of the above systems are not inflexible. The minimum detectable leak selected was based on one leak, occurring at the beginning of the mission and located at the farthest distance from the detector. Selection of a larger minimum detectable leak might be justified by assuming that the leak occurs at some later point in the mission. However, this can be offset by assuming that more than one leak can occur in one mission. Similarly, a lower minimum detectable leak might be justified by assuming multiple leaks per mission. However, this system will detect smaller leaks, if they are located closer to the detector. Thus the trade-off used to select the system operating point is not rigorous; however, it is reasonable.

The system weight could be further reduced by using fewer detector units of a higher sensitivity. However, this increases the coverage area per detector; in this case location might become a problem. In essence, the maximum coverage area allowable depends on the accessibility of the cabin wall of the particular vehicle for inspection of the leak. If the walls are readily accessible, a larger coverage area per detector could be considered.

It should be noted also that leaks smaller than the aforementioned minimum detectable leak could be detected at no increase in system weight by increasing the sensitivity of the detectors. Thus a detector of 1×10^{-7} mm-Hg sensitivity could detect leaks two orders of magnitude less than these minimum leaks. Hardware development of the system could lead to this higher sensitivity; however, the present design, based on a 1×10^{-5} mm-Hg detection sensitivity, ensures the feasibility of the approach.

A further weight reduction might be possible if the smaller and lighter acoustic sensors were used to detect and locate the leaks rather than the ion gauges. As previously reported, however, the basic feasibility of this concept has to be proven in a laboratory test. Since the acoustic leak detectors do show the potential for weight reduction, however, the concept should be proven or disproven in the laboratory before actual hardware development on a leak detection system is begun.

Therefore, it is recommended that laboratory tests be conducted to determine; (1) if an acoustic detector can pick up noise generated by a minute leak in the cabin wall; and (2), if this noise can be distinguished from noises made by equipment or men. If this is feasible, a comparison between the two systems should be made and the optimum system selected.

Once this is done, a leak detection, location and warning system should be developed along the following lines:

1. Development of a prototype leak detector unit including associated power or control circuitry.

    a. Developmental tests to establish the design and operating parameters of the system. The goal should be to obtain a maximum sensitivity of 1×10^{-7} mm Hg for the ionization gauge (or an equivalent leakage sensitivity of about 0.001 lbs/hr for the acoustic sensor) with minimum weight and power requirements.

    b. Breadboard design and testing of electronic components of the system.

2. Development of the warning and location systems.

3. Hardware design, including packaging of the detector, power and control circuits, and warning and location systems.

4. Manufacture and fabrication of the system.

5. Developmental tests for reliability, life, and the physical environments of vacuum, thermal, shock, vibration, acceleration, etc. to establish the capability of the system as flight hardware.

The end item of this program would be the design and fabrication of a leak detection, location and warning system that could be manufactured and used on current or future manned space vehicles.

Other developmental programs can be recommended also, namely development of the hardware for use in the different repair methods.

Development of the liquid and putty sealants should follow the same general procedures as outlined below:

1. Compounding formulations of liquid and putty sealants in accordance with the suggestions given in the text.

2. Testing of the compounds, with subsequent modifications (addition of resins to improve cure, consistency, adhesives, temperature characteristics, etc.), to meet the requirements of:

    a. Reliability of obtaining an effective seal

    b. Adhesion

    c. Durability and toughness (permanency of repair)

    d. Time to obtain sealing

    e. Resistance to shock, vibration, acceleration loads

    f. Resistance to space environment (vacuum, radiation, thermal)

    g. Toxicity

    h. Storage requirements

3. Selection of the optimum material

Development of the self-brazing plug and establishment of the design conditions for the mechanically fastened patch should also be undertaken. The following general outline will indicate the recommended program:

1. Development design of the plug and patch repair methods.

2. Testing, to establish design conditions needed for reliability of sealing, and capability of meeting the expected vibration, shock and acceleration loads.

3. Final design, manufacture and fabrication of flight-type qualified hardware that can be used in present or future space vehicles.

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Rpt Nr ASD-TDR-62-1015. REPAIR OF LEAKS IN AN AEROSPACE ENVIRONMENT. Final report, Feb 63, 167 pp. incl illus., tables, 18 refs.

Unclassified report

Our purpose was to determine the optimum method for detecting, location, and repair of leaks in a manned space vehicle cabin. Hazards that could cause leaks were defined. The requirements for the system were established and an optimum system evolved from a trade-off of many proposed techniques. Cold cathode ionization gauges mounted on the outside

(over)

1. Spaceship cabins
2. Plastic seals
3. Adhesive seals
4. Spacecraft leakage

I. AFSC Project 8170, Task 817005
II. Contract AF 33(657)-7852
III. General Electric Co., Philadelphia, Pa.
IV. D. J. Withey
V. Secondary Rpt Nr 62SD826
VI. Aval fr OTS
VII. In ASTIA collection

(i.e., vacuum or space side) of the cabin wall detects leaks through the wall by sensing an increase in pressure. Separate warning indicators are mounted in back on the inside of the wall so the crew can immediately know the location of the leak. The area of wall coverage for each detector-warning unit can be varied to suit an individual vehicle. Helium is the tracer gas.

Liquid sealant that cures to plastic film is used to repair junctions of component and cabin wall. Small punctures are repaired best with putty sealant that cures to form a tough, resilient plug. A self-brazing plug is optimum for larger punctures. Repairing large punctures in tight corners, a metal patch mechanically secured is optimum.

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